PERMISSIBLE DOSE FROM EXTERNAL SOURCES OF IONIZING RADIATION

Handbook 59

U. S. Department of Commerce
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U. S. Department of Commerce • Sinclair Weeks, Secretary
National Bureau of Standards • A. V. Astin, Director

Permissible Dose From External Sources of Ionizing Radiation

Recommendations of the
National Committee on Radiation Protection

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Preface

The Advisory Committee on X-ray and Radium Protection was formed in 1929 upon the recommendation of the International Commission on Radiological Protection, under the sponsorship of the National Bureau of Standards, and with the cooperation of the leading radiological organizations. The small committee functioned effectively until the advent of atomic energy, which introduced a large number of new and serious problems in the field of radiation protection.

At a meeting of this committee in December 1946, the representatives of the various participating organizations agreed that the problems in radiation protection had become so manifold that the committee should enlarge its scope and membership and should appropriately change its title to be more inclusive. Accordingly, at that time the name of the committee was changed to the National Committee on Radiation Protection. At the same time, the number of participating organizations was increased and the total membership considerably enlarged. In order to distribute the work load, ten working subcommittees have been established, as listed below. Each of these subcommittees is charged with the responsibility of preparing protection recommendations in its particular field. The reports of the subcommittees are approved by the main committee before publication.

The following parent organizations and individuals comprise the main committee:

American College of Radiology: R. H. Chamberlain and G. C. Henny.
American Medical Association: P. C. Hodges.
American Radium Society: E. H. Quimby and T. P. Eberhard.
American Roentgen Ray Society: R. R. Newell and J. L. Weatherwax.
National Bureau of Standards: L. S. Taylor, Chairman, and M. S. Norloff, Secretary.
National Electrical Manufacturers Association: E. D. Trout.
Radiological Society of North America: G. Failla and R. S. Stone.
U. S. Air Force: S. E. Lifton, Maj.
U. S. Army: J. P. Cooney, Brig. Gen.
U. S. Atomic Energy Commission: K. Z. Morgan and J. C. Bugher.
U. S. Navy: C. F. Behrens, Rear Adm.
U. S. Public Health Service: H. L. Andrews and E. G. Williams.
Representatives-at-large: Shields Warren and H. B. Williams.

The following are the subcommittees and their chairmen:

Subcommittee 1. Permissible Dose from External Sources, G. Failla.
Subcommittee 2. Permissible Internal Dose, K. Z. Morgan.
Subcommittee 3. X-rays up to Two Million Volts, H. O. Wyckoff.

Subcommittee 4. Heavy Particles (Neutrons, Protons, and Heavier), H. Rossi.
Subcommittee 5. Electrons, Gamma Rays, and X-rays above Two Million Volts, H. W. Koch.
Subcommittee 6. Handling of Radioactive Isotopes and Fission Products, H. M. Parker.
Subcommittee 7. Monitoring Methods and Instruments, H. L. Andrews.
Subcommittee 8. Waste Disposal and Decontamination. J. H. Jensen.
Subcommittee 9. Protection Against Radiations from Radium, Cobalt-60, and Cesium-137 Encapsulated Sources, C. B. Braestrup.
Subcommittee 10. Regulation of Radiation Exposure, L. S. Taylor, Acting.

Although most of the subcommittees have issued reports covering their particular fields of interest, the most basic report and the one upon which all others depend has not been issued until now. Even the permissible doses for radioactive material within the body are related back to basic information on the effect of external radiation in the form of moderate-energy X-rays or gamma rays. All codes of practice and other information relative to the safe handling of radioactive materials goes back to the basic concepts of permissible dose, which are discussed in this report.

Subcommittee 1 on Permissible Dose from External Sources under Dr. Failla's chairmanship was one of the first subcommittees to be established, and it has formulated some of the basic principles that have been used throughout the recommendations of the NCRP. However, for various reasons, the formal preparation of the report of this subcommittee has been delayed for a considerable time; even though the substance of the subcommittee's recommendations has been well known and in use for a number of years. No small item in the preparation of this report has been the very magnitude of the discussion and explanations that are thought to be essential to the complete presentation of the subject. It seems appropriate that a brief outline of the historical background of the work of this subcommittee should be presented.

The subcommittee to study the permissible dose from external sources was established at the initial reorganization meeting of the NCRP in December 1946. Following a considerable amount of preliminary correspondence and orientation, the first formal meeting of the present subcommittee was held in Chicago in June 1948. At this time, a number of basic and far-reaching decisions were made:

(1) To lower the then-existing permissible dose of 0.1

r/day by a factor of about 2 and to express it in terms of a week.

(2) To take the bloodforming organs as the most critical tissue and to apply the permissible limit of 0.3 r/week to these organs.

(3) To consider skin as a critical organ and to set the permissible dose for it at 0.6 r/week (at a depth of 7 mg/cm^2).

(4) To make the permissible dose for persons over 45 years of age double that for younger adults.

(5) To allow larger weekly doses for the hands and feet (1.5 r/week).

(6) To make a suitable recommendation about accidental exposure involving a single dose that might be as large as 25 r.

(7) To recommend an RBE (relative biological effectiveness) of 1 for X-rays, gamma rays, and beta rays; 5 for thermal neutrons; 10 for fast neutrons; and 10 for alpha particles.

In September 1948, the chairman attended some conferences in England at one of which he presented a report on "Permissible Exposure to Ionizing Radiations." During this visit, extensive discussions on the subject of permissible exposures were held with the British counterpart of our committee. These discussions lead to the informal acceptance of mutually agreeable permissible exposure values. Agreement was also reached on the concept of the critical organs for which permissible doses should be specified.

A preliminary report by this subcommittee was prepared during the summer of 1949 and, except for detail, did not differ very greatly from the present report. At about that time, there began a series of conferences including representatives of the United States, England, and Canada for the discussion of radiation safety problems with particular reference to atomic-energy operations. The first of these Tri-Partite conferences was held in Chalk River in September 1949, at which time the more essential recommendations of this subcommittee were accepted for exposure to external radiation. One basic change made at these meetings was the raising of the RBE for alpha particles to a value of 20. The permissible exposures to internal radiation and the maximum allowable radioactive content of air and water, initially adopted at the Chalk River Conference, were related back to the basic philosophy of permissible exposure developed by this subcommittee.

At the meeting of the International Commission on Radiological Protection in London in 1950, the essentials of the

Chalk-River recommendations were adopted. Immediately following the meetings of the ICRP, a second Tri-Partite conference was held at Harwell, England. Only minor changes were made in permissible radiation exposures.

The next full meeting of the subcommittee was held in Chicago in December 1951. All of the ideas incorporated in the present report were discussed then and were adopted in principle. Considerable time was spent on the wording of some of these recommendations and especially on the definition of permissible dose. The last meeting of the subcommittee was held in Cincinnati in December 1952. Most of the discussion at this meeting dealt with the detailed wording of the report and the general question of genetic effects. Considerable discussion centered about the per-capita dose for the whole population during its reproductive age. As this is a somewhat controversial subject and one involving a great deal of basic philosophy, it must be treated with great care. As the matter now stands, the geneticists of this subcommittee, together with some outside assistance, will prepare a full report of the genetic problem for consideration by the subcommittee and the main committee in the future.

The third Tri-Partite conference was held in Harriman, New York, in March 1953; no changes of basic philosophy developed at this conference. At the meeting of the International Commission on Radiological Protection in Copenhagen in 1953 the report of this subcommittee, with minor deletions of topics not of international interest, was used as a basis for the discussion. The general principles developed by this subcommittee, including the change to 0.6 r/week for the skin, were made a part of the most recent international recommendations.

The membership of the Subcommittee on Permissible Dose from External Sources, which prepared this Handbook, is as follows:

G. Failla, Chairman.
D. R. Charles.*
A. H. Dowdy.
H. L. Friedell.
H. J. Muller.
H. M. Parker.
C. Stern.
R. S. Stone.

A. V. Astin, *Director.*

*Participated in the early discussions.

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Permissible Dose from External Sources of Ionizing Radiation

1. Introduction

In 1934 the International Committee on X-ray Protection adopted 0.2 r/day or 1 r/week as the "tolerance dose." No statement was made as to whether the dose should be measured "in air" or on the surface of the body to include backscattered radiation. Following local practice in X-ray therapy in Europe and particularly in England, the tolerance dose was assumed to include backscatter; whereas in the United States it was taken to represent the dose measured in air. In all subsequent discussions of the problem by committees of American radiological societies and the Advisory Committee on X-ray Protection, it has been taken for granted that the tolerance dose was to be measured in air. The first specific statement to this effect appears in the 1946 "Safety Code for the Industrial Use of X-rays" prepared by the American Standards Association. Thinking in terms of air dose most of those concerned with the protection problem felt that 0.2 r/day was too high and from 1936 to 1948 the generally accepted value in this country was 0.1 r/day. If one bears in mind that backscatter increases the skin dose considerably in the range of X-ray quality commonly employed, the true difference between the British tolerance dose of 0.2 r/day or 1 r/week measured on the skin and the American of 0.1 r/day measured in air becomes quite small and indeed irrelevant.

At the time that the 0.1 r/day value was adopted and for some years thereafter, the chief concern was the protection of radiologists and technicians operating "deep therapy" X-ray machines at voltages of about 200 kv. It was realized that exposure of the whole body to the lower voltage X-rays used for diagnostic purposes was relatively safer, but for the sake of simplicity no distinction was made and the same limit was used for all qualities of X-rays (and gamma rays). In recent years, however, the situation has changed radically and a reexamination of the whole problem has become imperative.

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In the first place, ionizing radiations other than X- and gamma rays have come into common use. The conditions under which persons can be exposed to radiation are more numerous and varied. The distribution of radiation in the body—from external sources alone—may differ enormously, the radiation being limited to the surface layer of the skin in the case of ordinary alpha rays and the dose being at a maximum in the internal organs of the body in the case of multimillion-volt X-rays (initially not in equilibrium with the associated corpuscular emission). Also, more is known about the biological effects of radiation.

2. Radiological Terminology

2.1. *Ionizing radiation* is electromagnetic radiation (consisting of photons) or particulate radiation (consisting of electrons, neutrons, protons, etc.) usually of high energy, but in any case capable of ionizing air, directly or indirectly. The present report deals only with ionizing radiation. Therefore, the term "radiation" always refers to ionizing radiation.

2.2. *X-rays* (sometimes "X-radiation") are electromagnetic ionizing radiation.

In radiology X-rays are often classified according to the voltage at which they are produced. The following classification according to voltage range is generally understood.

Low-voltage X-rays: Voltage range up to 140 kv.
High-voltage X-rays: Voltage range 140 to 250 kv.
Supervoltage X-rays: Voltage range 250 kv to 3 Mv.
Multimillion-volt X-rays: Voltage higher than 3 Mv.

In this connection it is convenient to distinguish between the voltage at which the X-rays are produced and the energy of the X-ray photon. In this report *kv* or *Mv* refers always to the former, and *kev* or *Mev* refers to the photon energy. When the radiation is monochromatic, kev or Mev is generally used.

When the daily tolerance dose of 0.1 r was adopted it was thought that this was a conservative value, involving a large factor of safety. Observation of persons occupationally exposed to radiation within this limit has revealed no deleterious effects attributable to radiation. However, the period of observation is not yet sufficiently long to be *sure* that exposure at this rate can be continued safely throughout life. The results of large-scale experiments with mice and rats (and more limited experiments with other animals) lead to the conclusion that probably the factor of safety involved in the daily tolerance dose of 0.1 r is not as large as it was thought at first. From the genetic point of view

a revision downward is indicated because of the larger percentage of the total population now being exposed to radiation. An additional reason is provided by the large dose delivered to internal organs when the body is exposed to the very-high-energy radiations now available. On the other hand, local exposure of small regions of the body, or exposure to radiation of very low penetrating power, obviously involves less risk and some relaxation of the protection requirements is justified.

The present report deals primarily with the protection of persons occupationally exposed to ionizing radiation from external sources. An attempt has been made to cover most of the situations encountered in practice. However, it has not always been possible to make recommendations in quantitative terms. In such cases the recommendations are intended to serve as practical guides. The recommendations are based on presently available information and cannot be regarded as permanent. For this reason and on general grounds it is strongly recommended that exposure to radiation be kept at the lowest practicable level in all cases.

In this report frequent reference is made to the X-rays commonly used heretofore in radiological practice, that is, in the voltage range up to 200 or 250 kv. It is convenient to refer to these X-rays as "*ordinary X-rays.*"

2.3. *Roentgen rays* are X-rays usually produced by bombarding a (metallic) target with high-speed electrons in a suitable device.

2.4. *Gamma rays* are X-rays originating in the nuclei of atoms.

In general "X-rays" and "roentgen rays" are used interchangeably in radiology. The distinction indicated here is made simply for convenience, since it does away with the cumbersome repetition of the expression "X-rays and gamma rays".

2.5. *Quality of X-rays.* The term "quality" refers in a general way to the penetrating power of an X-ray beam.

a. *Soft X-rays* are X-rays of low penetrating power.

b. *Hard X-rays* are X-rays of high penetrating power.

2.6. *Half-value layer* (HVL). Quality is often expressed in terms of the half-value layer, which is the thickness of a specified material (usually aluminum, copper, or lead) required to decrease the dosage rate of a beam of X-rays at the point of interest to one-half of its initial value.

2.7. *Beta rays* (beta particles) are particulate ionizing radiation consisting of electrons or positrons traveling at high speed.

2.8. *Alpha rays* (alpha particles) are particulate ionizing radiation consisting of helium nuclei traveling at high speed.

2.9. *Neutrons* (or neutron rays) are particulate ionizing radiation consisting of neutrons that: either possess enough kinetic energy to set in motion, by impact, nuclei of atoms with sufficient velocity to ionize matter; or enter into nuclear reactions that result in the emission of ionizing radiation. The former variety is usually called *fast neutrons* and the latter *thermal neutrons*, with gradations of *epithermal* and *slow neutrons* in between.

2.10. *Heavy-particle radiation* is particulate ionizing radiation consisting of atomic nuclei of any mass traveling at high speed (protons, deuterons, helium nuclei, etc.). Alpha rays constitute a special kind of heavy-particle radiation.

2.11. *Specific ionization.* When a high-speed charged particle traverses matter, ions are produced along its path. The number of ion pairs per unit length of path is taken to represent the specific ionization of the particle at a given point in its trajectory or "track." In general, ionizing particles with different charges and of different energies may be present in the region of interest, and wide differences in specific ionization may occur. Because the biological effectiveness of an absorbed dose of radiation (q. v.) depends on the specific ionization, ideally one should know the specific-ionization spectrum of the dose in the locus of interest. This is not feasible at the present time and therefore in practice estimated average values are used. (See section 4.7.)

The number of ion pairs per unit length of track is generally determined in air. In radiobiology, however, one is interested in the transfer of energy to tissues, which includes the energy required to produce ions and the energy imparted to other atoms and molecules that are not ionized but become "excited." It is, therefore, more appropriate to speak of "linear energy transfer per unit length" (LET, according to R. E. Zirkle) than specific ionization. Since in practice values of LET are generally derived from the specific ionization in air, the distinction between the two is essentially a formal one in the present state of the art. In this report "specific ionization" is used because it is more generally understood. It is expressed in ion pairs per "micron of water," although the number of ion pairs really refers to the equivalent path in air. For convenience, values in terms of linear energy transfer (kev per micron of water) are included in table 3.

2.12. *Equilibrium with the associated corpuscular emission.* Ionization by X-rays is due almost entirely to the secondary

electrons liberated in the medium. When a parallel beam of monochromatic X-rays initially devoid of secondary electrons enters a slab of matter, a certain number of secondary electrons is liberated per unit thickness. These electrons travel some distance from the point of origin. Therefore, some reach the next thin layer of the material where more are liberated by the X-rays, and so on. Also, some may travel backwards and contribute to the number present in an intermediate layer. Beyond a certain depth, determined by the effective range of the secondary electrons of highest energy (in the forward direction), there is no further increase in the relative number of secondary electrons associated with the primary X-rays in successive layers. The radiation is then said to be "in equilibrium with its secondary electrons." This phenomenon is of importance in the measurement of X-ray dose in roentgens and in other respects relative to the protection problem. An analogous situation exists in the case of fast neutrons, where the secondary ionizing particles are recoil nuclei instead of electrons. The more general expression "in equilibrium with the associated corpuscular emission" is applicable to both cases.

2.13. *Dose.* In radiology a *dose* of ionizing radiation is a quantity of radiation. In this connection the term "quantity" represents the magnitude of the dose and may be expressed in various units. Since the adoption of the roentgen, it has been customary to express the magnitude of a dose of X-rays in roentgens. In recent years there has been an increasing tendency to regard a dose of radiation as the amount of energy absorbed by tissue at the site of interest per unit mass. Also, in physics "quantity of radiation" has always had a very special meaning (see section 2.15). To avoid confusion the International Commission on Radiological Units at its Copenhagen meeting in July 1953, recommended that a distinction be made between dose in a general sense and "absorbed dose." A new unit, the "rad" (see section 2.17) was recommended for the latter. To clarify further the terminology, the definitions given in sections 2.14, 2.15, 2.16, and 2.17 were adopted.

2.14. *Intensity of radiation* is the energy flowing through unit area perpendicular to the beam per unit time. It is expressed in ergs per square centimeter per second or in watts per square centimeter.

2.15. *Quantity of radiation* is the time integral of intensity. It is the total energy that has passed through unit area perpendicular to the beam and is expressed in ergs per square centimeter or watt-seconds per square centimeter.

2.16. *Absorbed dose* of any ionizing radiation is the amount of energy imparted to matter by ionizing particles per unit mass of irradiated material at the place of interest. It shall be expressed in "rads."

2.17. *The rad* is the unit of absorbed dose and is 100 ergs/g. One millirad (1 mrad) is one thousandth of one rad.

2.18. *The roentgen* is the quantity of X- or gamma radiation such that the associated corpuscular emission per 0.001293 g of air produces, in air, ions carrying 1 electrostatic unit of quantity of electricity of either sign. One *milliroentgen* (1 mr) is one thousandth of one roentgen.

2.19. *The rep.* Heretofore the rep (roentgen-equivalent-physical) has been used extensively for the specification of permissible doses of ionizing radiations other than X-rays or gamma rays. Several definitions of the rep have appeared in the literature but in the sense most widely accepted it is a unit of *absorbed dose* with a magnitude of 93 ergs/g. The difference in magnitude between the rep (93 ergs/g) and the rad (100 ergs/g) is negligible in the estimation of permissible doses. Therefore, the adoption of the rad to replace the rep does not necessitate a change in the numerical values of permissible doses stated in reps heretofore.

2.20. *Dosage rate.* Dosage rate, or dose rate, is the time rate at which a dose is administered, that is, dose per unit time. When the dose is administered intermittently one may speak of *an average dosage rate.* In the case of generators emitting radiation in pulses, the *instantaneous dosage rate* (during the pulse) may be very high while the average dosage rate may be low. Dosage rates are expressed in roentgens or rads per minute or multiples or submultiples of these units, e. g., milliroentgens per hour (mr/hr).

2.21. *Air dose and tissue dose.* In radiology a distinction is made between *air dose* and *tissue dose.* The former is determined as follows: Given a constant beam of ordinary X-rays, the dosage rate at the desired point in the center of the beam is determined by placing at this point a suitable measuring device, in air, and without the presence of other solid material that might scatter radiation into the device. Let us say that the dosage rate thus determined is 20 r/min. If a patient is now placed in the path of the beam with the surface of the skin proximal to the source at the same point in the beam, and a treatment of 10 min is given, the air dose administered to the patient is 200 r. The tissue dose at the surface of the skin is larger because at the point in question there is now, in addition, radiation scattered backward by the patient's body. Because of this "backscatter" the total surface dose might be 220 r or perhaps 300 r,

depending on factors irrelevant to the present discussion. Since for the same air dose the skin dose may vary considerably, it follows that, other conditions being equal, the biological effect produced in the skin is related more directly to the skin dose than to the air dose. The same conclusion applies with more force to the dose obtaining at different depths in the patient's body, since the difference between air dose and tissue dose may be very large.

In the past it has been customary to express tissue doses of X-rays in roentgens. In principle this can be done. However, it should be borne in mind that the roentgen is not a unit of *absorbed dose* even in air. The fundamental quantity indirectly specified in the definition of the roentgen is the number of ion pairs per gram of air. If the average energy lost by an electron per ion pair produced in air varies with the speed of the electron, the ergs per gram of air per roentgen will be different for different qualities of X-rays. (The figure of 84 ergs per gram of air, generally used, is only a reasonable approximation in the present state of the art.) Therefore, a tissue dose of 1 r should be interpreted to mean that the radiation at some particular point in the specified tissue has the potentiality of producing, under proper conditions, the number of ion pairs per gram of air required by the definition of the roentgen. There is no constant factor relating a tissue dose in roentgens and the absorbed dose in rads when the quality of the radiation varies greatly even for the same tissue.

It may be expected that in the future tissue doses will be expressed only in terms of energy locally absorbed, that is, in rads. This will avoid considerable confusion. For the purposes of the present report it is necessary to speak of tissue doses in roentgens for historical reasons and particularly in order to provide a basis for the transition to permissible absorbed doses in rads.

2.22. *Restricted meaning of dose.* It is important to note that dose (air dose, tissue dose, or absorbed dose) according to radiological usage, refers to exposure to radiation of a certain dosage rate for a certain length of time. The dose does not involve the size of the beam or, in other words, the area of the surface or tissue volume exposed to radiation. Accordingly, for the same dosage rate and time of exposure, the dose is the same whether one finger only, or the entire body, is exposed to the radiation.

3. Radiobiological Considerations

The detailed mechanism of the action of ionizing radiation on the living cell is not known. This statement, which is often made, leads the uninitiated to think that if "nothing" is known about the "mechanism" very little indeed must be known about the effects of radiation on man. One should bear in mind the sharp distinction between *knowing what* happens and *explaining how* it happens. Nobody knows what life is or how it originated but a great deal is known about the human body and its behavior in health and disease.[1] There is at present a large body of information about the effects of radiation on living organisms and on man. Every living cell can be damaged and killed by radiation *if the dose delivered to it is large enough.* Many different kinds of effect have been observed and studied. All such effects can be produced by *any* type of ionizing radiation provided it reaches the cell or organ in sufficient amount. Thus there is no uniqueness about any one type of ionizing radiation as to the kind of effect it will produce, although there is in some cases a difference in the dose required to produce a certain degree of effect by two different types of radiation, under otherwise comparable conditions. This is important because most of our information has been obtained from work with X-rays and can, therefore, be applied to other types of ionizing radiation by making suitable adjustments of dosage. Some of the pertinent biological effects and modifying factors are discussed below.

3.1. Biological Variability

All members of a group of apparently identical organisms, irradiated simultaneously under the same conditions, do not respond alike. If the dose is neither negligible nor overwhelming, some will show much more marked effects than others. This is attributed to "biological variability." It is not a unique characteristic of radiation effects, since it occurs in all cases in which a physiological stimulant of any kind (physical, chemical, or biological) is similarly used. It is nevertheless relevant in that it makes it necessary to deal with averages rather than with the individual. Since the factors that cause such variations are unknown, it is impossible to predict how a given individual will respond to a dose that is known to produce a certain effect on the average.

[1] To cite a homely parallel, many people can be good drivers without knowing anything about the mechanism of the automobile engine.

The simplest way in which to study this phenomenon is to give increasing doses of radiation to different groups of organisms and later determine the percentage survival for each group. Plotting percentage survival against dose one can determine the dose required to kill 50 percent of the organisms (the median lethal dose, MLD). Inspection of such a curve shows that a small percentage of the organisms will die with doses less than one-half of the MLD and a small percentage will survive doses more than twice the MLD. In other words, the spread in the dose required to kill one of the organisms picked at random is more than fourfold.

Similar biological variability has been observed in the case of much less severe effects. It is probable that it applies, also, in the range of very low doses where hardly preceptible effects may be expected; that is in the permissible-dose range. Therefore, if proper allowances are not made, a few individuals in a large group may show some effects. It is important to note, however, that there is no true idiosyncrasy to ionizing radiation and one need not fear that very small doses, harmless to others, will cause serious injury to him.

3.2. Latent Period

It is a prominent characteristic of the biological effects of ionizing radiation that there is generally a considerable delay between the exposure of an organism to radiation and the manifestation of the changes produced therein. The magnitude of the time delay depends on many factors—mostly biological—but in particular it depends on the magnitude of the dose. The larger the dose the earlier is the appearance of injury. This is important in the protection problem because, barring accidents or gross negligence, the doses are small and the latent period for some of the effects may be very long (25 years or more).

3.3. Recovery and Repair

When skin is wounded by mechanical means, recovery is brought about essentially by restoration. The repair process is then one of replacement of destroyed tissue elements. If skin is damaged by radiation to the extent that cell destruction occurs, healing takes place in substantially the same way. There is, however, another process of recovery that may be attributed to recuperation from radiation damage, occurring in the individual cells. This is illustrated by the following example.

Let us say that with a given quality of X-rays, skin erythema of a certain degree is produced by a skin dose of 700 r administered in 1 hr. Experiment shows that to produce the same effect with two (short) treatments separated by an interval of 24 hr, each dose must be 535 r; that is, a total of 1,070 r. (For shorter time intervals the difference is less and for longer ones it is greater.) Evidently some sort of recovery from the effects of the first 535 r has occurred in a period of 24 hr. Since 700 r given at one time produced the erythema in question, the effective dose remaining from the first treatment of 535 r must have been 165 r. In this case, recovery in 24 hr overcame the effect of 370 r.

That this kind of recovery takes place in the individual cells is not obvious from this example in which both the tissue and the reaction are complex. However, a similar phenomenon has been observed in unfertilized marine eggs, in which case it has been shown further that the recovery process takes place in the cytoplasm. In the case of skin erythema the important point is that recovery—in this special sense—takes place long before the manifestation of the injury, since the height of the erythema reaction occurs about three weeks after the single 700 r treatment. Therefore, whatever the process may be (and whether it takes place within the cell or not), it tends to cancel the effect of the radiation in the early stages of the biological reaction. The distinction between recovery and repair (or restoration) is not always made in radiology. Therefore, in common usage "recovery" may refer to the combined result of recovery and repair. The same practice will be followed in this report unless specifically stated otherwise.

If the dose is not too large, the organism will recuperate from the effects of radiation. Remembering that the latent period for some of the effects may be very long, it is difficult to say whether complete recovery has occurred at any time. Recovery from effects of fairly large doses that appear within the first few weeks, may take place within a few months and appear complete. Whether complications will develop later—much later—depends on many factors and is generally impossible to predict. It may be taken for granted, however, that some permanent changes in some tissues have occurred, if for no other reason than the irreversible effect of radiation on chromosomes and genes. Thus, some of the wart-like processes that appear in over-irradiated skin are remarkably permanent and may well be the result of somatic mutation of one or more of the mother cells of the skin in that region.

3.4. Time Factor

When the exposure is extended over a long period of time, considerable recovery may take place during the period of exposure. A larger dose is then needed to produce the same degree of effect as is produced with a dose administered in a short time. The importance of the "time factor" of a dose of radiation depends, among other things, on the biological properties of the cells and tissue under consideration and on the kind and degree of effect studied.

A skin dose of 700 r of hard X-rays will produce a slight erythema on the skin of the average person if it is given in a short time, but will produce no apparent changes at all if administered in fractional amounts or continuously over a period of 1 month. There is in this case an interplay between the rate at which damage is caused and the rate at which recovery takes place. To produce a mild erythema by intermittent irradiation over a period of 1 month, the total dose would have to be about 1,900 r instead of 700 r. The reason is that in the skin constant renewal takes place normally to take care of normal wear and tear and recovery is rapid. In tissues in which cells are dividing slowly, recovery is not so rapid and the time factor plays a less important part.

In general, radiation effects are more marked the shorter the time during which the given dose is administered. A well established exception to this rule is the production of gene mutations, which has been shown to be independent of the time distribution of the dose within very wide limits. It is possible that for some effects in some tissues (e. g., skin cancer) optimal values of total dose and time of administration exist, but practically nothing is known about this. As a rule one may expect marked differences in response when the time of administration of the same dose is varied from a small fraction to a large multiple of the life cycle of the cells in the tissue under consideration. When the whole organism is irradiated the problem becomes much more complex. Differential recovery in the cells, tissues, and organs of the body comes into play and the resultant over-all effects are then influenced both in kind and degree by the time factor.

The same dose may be given by continuous exposure at low dosage rate or by intermittent (fractional) exposures of short duration and high dosage rate. The two are usually not strictly equivalent, but within limits, which may be narrow or wide depending on circumstances, the difference is too small to be of practical significance. When the expo-

sure is extended over a period of many years, no distinction need be made between continuous and intermittent exposure of the same total dose provided the fractional doses are essentially of equal magnitude and closely spaced. The proviso makes each fractional dose very small in comparison to the total dose.

3.5. Radiosensitivity

Some living organisms may be killed by small doses of radiation, while others will survive much larger doses (of the order of one million roentgens in the case of virus particles). However, in laboratory mammals and man the spread in the lethal dose for different species is quite narrow, perhaps within a factor of three or four. On the other hand, individual cell types in a mammal differ greatly in radiosensitivity; young rapidly dividing cells being most sensitive and fully differentiated nerve cells being most resistant to radiation.

Radiosensitivity of a living cell is influenced by many intrinsic and extrinsic factors (which cannot be discussed here). For this reason all pertinent factors must be included in any quantitative statement of radiosensitivity.

In the protection problem both the absolute and relative radiosensitivities of the various body cells, tissues, and organs are important. Since the effect of modifying factors on different biological entities is generally different, the relative radiosensitivities are also influenced by these factors. This introduces additional complications. The time factor, for instance, plays an important part when recovery takes place in one tissue and not in the other of the two under comparison, or in general when the recovery rates are different. In this case, the radiosensitivities of the two tissues may be nearly equal or quite different, depending on the rate at which a dose is administered. The specific ionization of the radiation also plays a part. This, however, will be discussed under the heading of relative biological effectiveness.

Many attempts have been made to alter the radiosensitivity of cells, tissues, and whole animals by physical or chemical means. Considerable progress has been made, but practical application to the protection of personnel must await further developments.

3.6. Relative Biological Effectiveness (RBE)

It has been stated that all ionizing radiations are capable of producing the same kinds of biological effect. However, in their ability to produce some of these effects certain radia-

tions are more "effective" than others, in the sense that a smaller absorbed dose of these radiations is required to produce a given degree of effect. This is generally referred to as *biological effectiveness*. Knowledge of the biological effectiveness of radiation is of considerable practical importance since it determines essentially how reliably protection data pertaining to X-rays can be applied to other types of ionizing radiation.

In general for the same tissue dose, densely ionizing particles produce more marked effects than are produced by electrons. In the case of gene mutations, however, the effectiveness is about the same or in favor of electronic radiation. In experiments in which mice have been exposed to penetrating X-rays or fast neutrons under comparable conditions, the lethal effectiveness of neutrons has been found to be four or five times greater than that of X-rays. That these differences in effectiveness are due to differences in specific ionization and not to differences in mass of the ionizing particles, is shown by experiments with very-high-energy protons or deuterons of low initial specific ionization, in which case the biological effects are comparable to those of low-energy electrons.

Of particular importance is the fact that the *relative* biological effectiveness varies with the kind and degree of effect, the type of cell or tissue, the organism studied, etc., and with extrinsic factors such as the time distribution of the dose (time factor). This is related to the vagaries of radiosensitivity.[2] If all the cell types of the fully developed human body were listed in the order of increasing radiosensitivity with respect to the lethal action of X-rays under certain experimental conditions, definite values of relative radiosensitivities could be obtained. If the same determinations were made by using radiation of high specific ionization (e. g., fast neutrons), the order in which the different cell types would be listed would not be very different; but the quantitative relationships between the radiosensitivities of certain cell types (i. e., the relative radiosensitivities) would be quite different. The relative radiosensitivities would again be different if a different criterion of effect were used, or, in general, whenever a pertinent factor is changed significantly. This means, in practice, that when the whole body is irradiated with X-rays or fast neutrons in such a way that the dose distribution throughout the body is iden-

[2] The concept of biological effectiveness could be dispensed with by attributing differences due to differences in specific ionization, to changes in radiosensitivity. Thus, saying that fast neutrons are more effective than X-rays in damaging the lens of the eye, is equivalent to saying that the lens of the eye is more sensitive to fast neutrons than to X-rays.

tical, and the exposures are adjusted in the ratio of an "average" relative biological effectiveness, the damage to any two corresponding organs will not be the same. To be sure, in the case of animals one may determine experimentally under comparable conditions the lethal doses for X-rays of a certain quality and for fast neutrons of a given energy spectrum, and then derive a numerical value of the RBE. It is important to note, however, that the relative damage to the different organs in the two cases cannot be expected to be identical. In fact it is known from such an experiment performed with mice, that in the case of fast neutrons most of the animals developed cataracts before they died, while in the case of X-rays few did. The RBE of fast neutrons with respect to X-rays under the conditions of this experiment is, therefore, considerably higher for cataract formation than for lethality. In a similar experiment in which the mice received daily treatments over a long period of time, the effectiveness of fast neutrons in producing cataracts was found to be even higher. This shows that the RBE of fast neutrons for cataract formation in mice depends on the time factor.

3.7. Differential Variations

It will be seen from the preceding section that in dealing with the biological effects of ionizing radiation in general, whether we think in terms of radiosensitivity or biological effectiveness, we are inexorably "plagued" by "differences in differences." The typical problem involves two distinct biological entities and two radiations of significantly different specific ionizations. To simplify the discussion the results of a hypothetical experiment involving the lethal action of X-rays and fast neutrons on cell types A and B, are given in table 1. It will be seen that cell type B is more radioresistant than A in both cases. However, the difference is by a factor of 2 in the case of X-rays and by a factor of 2.5 in the case of neutrons. In other words there is a difference in the difference. From the other point of view, fast neutrons are more effective than X-rays in killing both cell types A and B. However, the RBE is 5 in the case of cell type A and 4 in the case of B. Again there is a difference in the difference. For the sake of brevity the descriptive expression "differential variations" will be used in referring to this phenomenon.

Differential variations may occur with only one type of radiation when another parameter is different. In the hypothetical example given in table 2 the radiation is the

TABLE 1. *Illustration of differential variations with respect to specific ionization*

	Lethal dose in rads		Dose ratio—X-rays/neutrons
	X-rays	Fast neutrons	
Cell type A	1, 000	200	5
Cell type B	2, 000	500	4
Dose ratio, B/A	2	2. 5	----

TABLE 2. *Illustration of differential variations with respect to time factor*

	Lethal X-ray dose in rads		Dose ratio—Long/short
	Short exposure	Long exposure	
Cell type P	1, 000	1, 500	1. 5
Cell type Q	2, 000	2, 500	1. 25
Dose ratio, Q/P	2	1. 67	----

same but the time factor is different. To distinguish between the two examples given here (tables 1 and 2), it may be said that the first illustrates differential variations with respect to specific ionization and the second illustrates differential variations with respect to time factor. There are, of course, many other types of differential variations; for instance, with respect to age, oxygen tension, temperature, etc. It should be noted in this connection that, in order to attribute differential variations to a definite factor, all other factors and conditions must be the same.

3.8. Whole-Body Irradiation

When the entire body is exposed to penetrating radiation, all organs are irradiated; but some receive larger doses than others. The difference in dose from organ to organ depends on the penetrating power of the radiation and on geometrical factors, such as the distance of the body from a source of small dimensions, the depth of the organ, etc. The local and

overall effects produced are then largely dependent on the tissue dose distribution throughout the body—which in practice may vary enormously. The problem is further complicated by differential variations that occur when the tissue dose distribution is the same but some other factor is different (e. g., the time factor or the specific ionization of the radiation).

It is generally assumed that the effect produced in any given tissue or organ is due entirely or largely to the tissue dose delivered to it. When the entire body is irradiated more or less uniformly, innumerable changes can occur and it is conceivable that an organ may be damaged because some other organ does not function properly, or because some deleterious agent produced by the radiation has been released into the circulatory system. That something of this nature does occur is indicated by experiments in which some organ (e. g., the spleen) or part of the body has been shielded from radiation during the exposure of the rest of the body and the animal has been able to survive an otherwise lethal dose. However, this does not lessen the importance of the distribution of radiation within the body. Tissues and organs that are known to be damaged directly by radiation lie at different depths in the body. Furthermore, in the absence of any definite knowledge about indirect effects we must assume that the dose received by a certain organ is largely responsible for the damage manifested by that organ. An extreme example can be mentioned in this connection. Experiment has shown that very large doses of beta rays administered externally to rabbits damage the skin seriously without causing any changes in blood count; because the radiation is not penetrating enough to reach the bloodforming organs. In very small animals this would not be the case.

The situation concerning exposure of the entire body to radiation may be summarized as follows: The distribution of radiation within the body determines the doses received by the different organs. The effects produced in each depend largely on the dose and the radiosensitivity of the organ. The combination and interaction of all these effects determine the overall injuries manifested by the individual. Variations of factors that determine the relative effects in different organs of the body will modify the over-all effects. All other conditions being the same, differences in over-all effects, in degree and/or in kind, can be expected: (1) When the distribution of radiation within the body is different, because the relative doses received by the organs will be

different; (2) when the total dose is different, because all organs are affected more by larger doses and some organs that are unharmed by small doses will be injured by larger doses; (3) when the time of administration of the total dose is different, because of differential variations due to changes in the relative radiosensitivities of the organs (largely due to inherent differences in recovery rates for the different organs); (4) when the instantaneous dosage rate or the dose fractionation with respect to time is different, because of possible differential variations due to changes in relative radiosensitivity; (5) when the specific ionization is different (two different kinds of radiation), because of differential variations due to difference in RBE; (6) when the tissue depth-distribution of the specific ionization is different, because the RBE at different depths will be different; (7) when, in general, any factor that introduces differential variations is different.

It is obvious from the foregoing that the results of experiments in which animals of very different size are exposed to the same beam of radiation are not strictly comparable. *A fortiori*, great care must be exercised in applying the results of such experiments to man—if for no other reason than because the distribution of radiation in the body is apt to be quite different. However, it should be noted that with ordinary X-rays the distribution of radiation in a man's body would be less uniform and therefore less effective in producing general injury, than in the case of ordinary laboratory animals (mice, rats, or rabbits) exposed to the same beam. This per se makes extrapolation to man on the safe side, but of course many other factors must be taken into account.

3.9. Genetic Effects

Ionizing radiations are capable of producing changes in individual genes and chromosomes in all nucleated body cells. The subsequent manifestations of these primary effects (when sufficiently marked) are generally deleterious to the individual in his lifetime and to future generations when they occur in the germ cells. It has been shown experimentally that genetic changes can be produced with low doses of radiation. The frequency of occurrence increases linearly with the dose in the case of gene mutations and is independent of the duration of the exposure. In the case of chromosome breaks with subsequent abnormal union of some fragments (e. g., translocation) the frequency of occurrence depends also on the dosage rate, within certain limits. It is evident that whether an individual is par-

ticularly susceptible or not, some injury of this type is unavoidable. Some cells in his body, including some germ cells, will be genetically altered. However, *genetic changes of the same kind occur spontaneously* and one is not dealing with a mysterious injury of an entirely new type. The main point is to control exposure in such a way that the eventual manifestation of genetic injury is not too large in comparison with the occurrence of spontaneous genetic abnormalities. Insofar as the welfare of the race is concerned (i. e., future generations) gene mutations with inconspicuous manifestations play the most important part. The controlling factor is then the number of undesirable genes (both spontaneous and radiation-induced ones) present in the general population in which intermarriage occurs. It is, therefore, immaterial in this case whether in one generation the undesirable genes are present largely in a few individuals or are distributed throughout the population in correspondingly smaller number per individual. Accordingly, the amount of radiation received by the gonads of one individual up to the time of conception of the last child in his family, can be very large without noticeably damaging the population as a whole—provided that only a very small fraction of the whole population is exposed to this extent. Under present conditions and for some time to come, genetic damage to the population as a whole in future generations is not a limiting factor in setting up a permissible level for occupational exposure to ionizing radiation. For other reasons the level must be considerably lower than might be set on the above grounds. However, it is well to bear in mind that this factor assumes greater importance as the percentage of the population exposed to radiation increases. Moreover it should be realized that any amount of radiation received by the gonads of even a few individuals before the end of their reproductive period is likely to add to the number of undesirable genes present in the population. While the majority of these genes may have no recognizable effects for a number of generations, practically all are potentially bound to result eventually in undesirable conditions.

Considering now genetic damage manifestable in the lifetime of the individual or in the first-generation offspring, it is obviously necessary to limit the exposure of *every* individual. Chromosomal damage in somatic cells may be responsible, at least in part, for radiation injuries that become evident in the lifetime of the exposed individual. Very little is known about this (which in essence has to do with the mechanism of the action of radiation), but a great deal is

known about the observable effects themselves. For purposes of protection it is sufficient to choose a level of exposure that will effectively prevent the occurrence of the injurious effects no matter how they are produced. Genetic changes manifestable in the first-generation offspring are of concern to the exposed individual, since his well-being depends in no small degree on psychological factors in his family life. Sterility, stillbirths, and abnormal children may be produced by overexposure to radiation. Most of the information on these effects has been obtained from animal experiments, but it may be taken for granted that the same effects occur in man. However, practical experience indicates that undesirable effects of this nature, if present, have not been so marked as to attract attention, in the case of radiologists and technicians who have been occupationally exposed to radiation—sometimes excessively, as shown by other more obvious injuries. It should be noted in this connection that sterility, stillbirths, and abnormal children occur in nature spontaneously or for reasons in which exposure to radiation plays no part. In any particular instance, it is therefore extremely difficult to attribute any such effect to radiation.

3.10. Effect on Lifespan

Experiments performed with laboratory animals (chiefly mice and rats) show that exposure to radiation *in sufficient amounts* shortens the average lifespan. This has been found to be true under a variety of different conditions of irradiation, including daily exposures and single treatments. In all these experiments survival curves of the irradiated animals are compared with survival curves of a control group. Because there is always considerable biological variability, small differences in survival curves may occur in the control groups themselves. Hence small differences caused by exposure to radiation are obscured and cannot be considered significant. In order to establish small differences it is necessary to use very large numbers of animals (of the order of thousands rather than dozens) and to take many precautions. Because the number of animals used in such experiments has been too small, it has been customary to extrapolate to smaller doses the results obtained with doses so large that significant differences could be established. Following this procedure it may be shown that an appreciable shortening of the lifespan occurs in mice and rats exposed daily to doses of X-rays in the neighborhood of 0.1 r. Whether this extrapolation is justified or not cannot

be decided at the present time. Experimental data on lifespan obtained with other laboratory animals are quite fragmentary and extrapolation to low daily doses is even more uncertain. No quantitative information is available in the case of man. Because the possibility of a shortening of the lifespan in man by small daily doses cannot be excluded, the available experimental data may be assumed to indicate the desirability of lowering the permissible daily dose for lifetime exposure of the whole body to penetrating radiation.

Essentially the same situation exists in connection with the interpretation of other gross effects produced by continued exposure of the whole body to penetrating radiation. Small effects are difficult to determine accurately unless very large numbers of experimental and control animals are used.

4. Protection Criteria

4.1. Acceptable Risk

As a matter of principle it is sound to avoid all unnecessary exposure to ionizing radiation, because it is desirable not to depart from the natural conditions under which man has developed by evolutionary processes. However, man has always lived in a field of ionizing radiation due to the presence of radioactive material in the earth and to cosmic rays. Whether exposure to this level of radiation is beneficial or deleterious to man (and the race) is a matter of speculation. The obvious fact is that it cannot be avoided and it is, therefore, normal for man to live in this environment. We have then a lower limit of continuous exposure to radiation that is (unavoidably) tolerated by man. There is, on the other hand, a much higher level of exposure that is definitely known to be harmful. Between these two extremes there is a level of exposure, in the neighborhood of 0.1 r/day, that experience to date shows to be safe for the individual concerned; however, the time of observation of large numbers of people exposed at this rate under controlled conditions is too short to permit a categorical assertion to this effect. It should be noted in this connection that lowering the level of exposure by a factor of two, or even ten, does not materially alter the situation insofar as making a positive statement of absolute safety is concerned. The only statement that can be made at the present time about the lifetime exposure of persons to penetrating radiation at a permissible level considerably higher than the background radiation level, but within the range of radiological experience, is that appreciable injury manifestable

in the lifetime of the individual is extremely unlikely. It is, therefore, necessary to assume that any practical limit of exposure that may be set up today, will involve some risk of possible harm. The problem then is to make this risk so small that it is readily acceptable to the average individual; that is, to make the risk essentially the same as is present in ordinary occupations not involving exposure to radiation.

Even on this more liberal basis the solution of the problem is still difficult. Lack of extensive long-term practical experience under controlled conditions precludes an *a priori* accurate determination of the risk for any exposure level that may be adopted. The only thing that can be done at present is to adopt a value that in the light of all available information can be confidently expected to conform with the criterion of acceptable risk.

The acceptability of a risk by the average person depends largely on the probability of escaping injury altogether. It is well known that susceptibility to radiation damage varies markedly among apparently identical members of a large group (biological variability). Therefore, for any given type and degree of injury there is an exposure level that will produce such injury only in the most susceptible individuals. If the injury is of minimal degree, the others will not be aware of any injury at all. Accordingly, with a sufficiently low exposure level the probability of escaping injury altogether can be made very high. Because there is at present no way of determining in advance who is most susceptible to radiation, each person has, in effect, the same chance of escaping injury as anybody else. Under these conditions and in this sense, then, the risk of radiation injury has essentially the same characteristics as more common risks readily accepted by the average person in his ordinary pursuits.

Because the risk under discussion is one arising from lack of factual knowledge about the ultimate effects of long continued exposure at low levels, it may be pointed out that in one respect this risk is much more acceptable than others in that any possible deleterious effect will become apparent only very late in life. This is substantiated by the histories of numerous radiologists who *were obviously overexposed* and eventually died of anemia or leukemia. Until the final episode, late in life and usually of short duration, they showed no apparent signs of any abnormal physical or mental deterioration. This is also true of those who *must have been overexposed*—judging from the conditions under which they worked—and did not develop a terminal disease attributable to radiation. (Cases in which cancer developed early in life following gross local overexposures are in a different category.

Under present conditions such overexposure cannot occur except through accident or gross negligence. It constitutes a different kind of risk from the one discussed here, which has to do with what might happen to a very susceptible individual if long continued exposure at a level considered to be permissible today should prove to be too high in his particular case.) In another respect the risk is less acceptable to the average person. This refers to the fear of possible damage transmitted to the offspring. For this reason it is important that genetic damage to the individual, as well as to the race, be considered in the setting up of permissible limits of exposure.

In connection with the protection problem there has been a tendency in the past to assume that any detectable biological change produced by radiation is deleterious. This conservative attitude is desirable in the absence of conclusive evidence to the contrary. However, as the means of detection become more refined it will be possible to determine changes of smaller and smaller magnitude. Also new kinds of effect will be found. Therefore, at some point it will become necessary to decide what degree of any particular change is to be considered injurious. Because obtaining conclusive evidence of harmlessness is practically impossible without conducting long-term experiments, a tentative decision will have to be made beforehand. Reaching this conclusion on the basis of the conservative criterion mentioned above, might well lead to the repeated lowering of permissible limits of exposure for reasons that may prove to be invalid much later. Accordingly, some relaxation of this rigid criterion appears desirable. In any particular case the decision should be reached on the basis of the probable influence of the slight change under consideration on the health and well-being of the individual in the light of existing biological and medical knowledge.

4.2. Critical Tissues

X-rays have been used extensively for the diagnosis and treatment of disease in man for about 50 years. Many doctors and technicians have been continually exposed to them for years. Some have suffered injuries of various types and degrees, leading to premature death in some instances; and some have shown no ill effects. There is, therefore, a very large background of practical experience based on observations made on human beings. Unfortunately, accurate measurements of X-rays could not be made in the early days and consequently the correlation of dose and effect

cannot be made directly in the case of those occupationally exposed during the first 25 years or so. It is in that period that most of those who later showed marked radiation changes were exposed. Nevertheless, it is possible to reconstruct approximately the conditions under which work was carried out in those days and to get some rough idea of the doses involved. Therefore, radiological experience provides data most directly applicable to the protection problem. The results of a vast amount of laboratory experimentation, interpreted in the light of radiological experience, furnishes additional pertinent information.

a. Skin

For the purpose at hand it is necessary to consider only injuries initially of a minor degree; because in the present state of the art no serious acute injuries should occur except through accident, inexcusable ignorance, or reckless disregard of protection rules. Also, the case of most practical importance is one in which the exposure occurs at a slow intermittent rate over a period of years. There have been many individuals exposed in this way who developed cancer of the skin definitely attributable to radiation. In all such cases the skin manifested typical radiation changes and cancer developed later—sometimes after many years—in one or more of the affected areas. It is important to note that in some cases the precancerous lesions were of a very minor character and the skin in the immediate vicinity had a practically. normal appearance. According to clinical experience to date, cancer always develops in some area in which abnormal cell growth has been apparent for some time. Numerous such abnormal skin areas have been removed surgically and histological examination has established the fact that they were not cancerous. Other areas initially similar to these have been found to be cancerous.[3] A similar situation is known to exist when cancer of the skin develops in persons exposed to sunlight and dust in a dry climate (e. g., Australian farmers). Therefore, insofar as the skin is concerned, the essential criterion of protection is prevention of cancer attributable to radiation. Clinical experience indicates that cancer arises in skin that has been permanently damaged. Therefore, exposure to radiation should be kept below the level at which permanent skin changes visually detectable by a dermatologist or a cancer specialist are likely to be produced in the lifetime of the individual.

[3] It may be well to point out that some people with marked skin abnormalities caused by radiation, and of very long duration, have not developed cancer of the skin.

Permanent damage of the kind envisaged here occurs when some skin cells in the basal layer of the epidermis are altered and no longer function normally. Cells closer to the surface are constantly being replaced by new ones and, therefore, direct damage to these cells is inconsequential. They are also much more radioresistant.

Experience has shown that in badly overirradiated hands in which cancer finally develops, the neoplasm arises almost invariably in the skin (and is usually of the squamous cell type). In these cases, mainly radiologists who had done fluoroscopy for many years, the absorbed dose in the bones of the fingers must have been considerably larger than in the skin, because of the small difference in depth and the much greater absorption by bone of the soft X-radiation used. Because it is known that radiation can produce bone tumors, it must be concluded that, under the conditions obtaining in these cases of exposure of the hands, skin is the critical tissue as regards the danger of eventual cancer formation. When the radiation is of such low penetrating power that it is almost entirely absorbed by the skin, this organ is also the critical tissue, even for exposure of the whole body.

b. Bloodforming Organs

When the whole body is exposed to penetrating radiation, the relative radiosensitivity of different tissues and organs comes into play. Under certain conditions of exposure the distribution of radiation throughout the body could be nearly uniform, in which case the greatest primary damage from overexposure would occur in the most sensitive tissue. The manifestation of injury would not necessarily be in the same tissue or organ. In view of the delicate balance of biological processes that is required to maintain health and the complexity of these phenomena in the human body, it is impossible at the present time to appraise the relative importance of possible damage to different organs in relation to an over-all deleterious effect of radiation. Nevertheless it is possible to decide what may be considered to be the critical tissue in the case of exposure of the whole body to penetrating radiation, on the basis of observations made on radiologists and X-ray technicians.

The incidence of leukemia in radiologists has been found to be considerably higher than in other physicians. While the number of cases is really too small to permit reliable statistical conclusions, other evidence (such as animal experiments and the well known high radiosensitivity of the bloodforming organs) supports this finding. Therefore, it

is well to assume that a causal relation existed in these cases. Because the exposure began many years ago, it is impossible to estimate the amounts of radiation received in their lifetimes. However, in many cases the individual enjoyed normal health and was not aware of any injury (except possibly for skin changes caused by local overexposure) until the leukemic process started late in life. It may be concluded, therefore, that in susceptible [4] individuals leukemia may result from whole-body exposure to radiation in amounts too small to cause subjective indications of general radiation damage. Accordingly, in the case of whole-body exposure to penetrating radiation it may be well to take prevention of radiation-induced leukemia as the criterion of protection. The bloodforming organs then constitute the critical tissue in this case. If the development of radiation-induced leukemia is analogous to the induction of cancer of the skin, it may be supposed that some permanent damage of the bloodforming organs precedes the appearance of the leukemic process. Therefore, exposure to penetrating radiation should be kept below the level at which appreciable permanent damage of the bloodforming organs may be produced in the lifetime of the individual.

c. Other Organs

Quantitative knowledge of the relative radiosensitivities of all the organs of the body is not sufficiently accurate and complete to permit the categorical statement that the bloodforming organs are the most radiosensitive. Certain it is, however, that considering the ease with which blood changes can be produced and the seriousness of the consequences of damage to the bloodforming organs, they constitute the principal tissue to be protected. When the whole body is irradiated essentially uniformly and the dose is such as will produce slight changes in blood count, other tissues may be affected as well. However, radiological experience reveals that, either the change is imperceptible, or the consequences therefrom are inappreciable in the lifetime of the individual. Therefore, it is safe to assume at present that the bloodforming organs constitute the most critical organs.

From the point of view of genetic damage manifestable in future generations, the gonads, of course, constitute the critical tissues "par excellence." However, it has already been pointed out (q. v.) that under present conditions of

[4] That is, "susceptible to radiation-induced leukemia." Some of the radiologists had also marked skin changes on the hands of very long duration, but did not develop cancer of the skin.

occupational exposure to radiation, genetic damage to the population as a whole is not a limiting factor. Nevertheless, the gonads must be considered as critical tissues because of the danger of sterilization [5] or impairment of fertility. In this respect the radiosensitivity of the gonads—ovaries and testes— may be assumed to be of the same magnitude as that of the bloodforming organs.

Radiological experience does not indicate that the lens of the eye is particularly sensitive to X-rays, with respect to cataract formation. Cataracts have been produced in patients by large doses administered to treat cancer in the neighborhood of the eye. However, the incidence of cataracts in radiologists and technicians exposed to large X-ray doses (as indicated by severe damage in the skin of the face) has not been high enough to attract attention. On the other hand some physicists exposed to neutrons have developed cataracts without showing appreciable skin changes or permanent loss of hair. Also, the incidence of cataracts among the survivors of Hiroshima and Nagasaki has been high. Therefore, the lens of the eye must be considered to be a critical tissue especially in the case of exposure to radiation of high specific ionization. It may be well to point out in passing that this is a case in which differential variations obviously introduce difficulties in the application of information obtained from exposure to X-rays to exposure to a different type of radiation.

4.3. Permissible Dose

The concept of a tolerance dose involves the assumption that if the dose is lower than a certain value—the threshold value—no injury results. Since it seems well established that there is no threshold dose for the production of gene mutations by radiation, it follows that strictly speaking there is no such thing as a tolerance dose when all possible effects of radiation on the individual and future generations are included. In connection with the protection problem the expression has been used in a more liberal sense, namely, to represent a dose that may be expected to produce only "tolerable" deleterious effects, if any are produced at all. Since it is desirable to avoid this ambiguity the expression "permissible dose" is much to be preferred.

It is now necessary to give this expression a more precise meaning. In the first place it is well to state explicitly that the concept of a permissible dose envisages the *possibility* of

[5] Sterility is loss of power to produce offspring; impotence is loss of power to copulate. Potency is not affected by radiation unless the dose is extremely large.

radiation injury manifestable during the lifetime of the exposed individual or in subsequent generations. However, the *probability* of the occurrence of such injuries must be so low that the risk would be readily acceptable to the average individual. *Permissible dose may then be defined as the dose of ionizing radiation that, in the light of present knowledge, is not expected to cause appreciable bodily injury to a person at any time during his lifetime.* As used here "appreciable bodily injury" means any bodily injury or effect that the average person would regard as being objectionable and/or competent medical authorities would regard as being deleterious to the health and well being of the individual. "Dose" is used here in its radiological sense and particularly as tissue dose in the irradiated tissue, organ, or region of interest. What constitutes the region of interest depends on the conditions of exposure and must be taken into account in assigning numerical values to the permissible dose or doses applicable to a given set of conditions.

4.4. Permissible Weekly Dose

The most important practical case is that of intermittent or continuous exposure of the whole body at essentially constant rate over an indefinite period of time, that is, a large fraction of the lifespan. Since the duration of the exposure is indefinite, it becomes necessary to specify the permissible dose in terms of dosage rate. However, dosage rate is generally used in a more restricted sense to indicate the rate at which a single dose or an increment of a dose is administered. In the case under discussion the daily dose may be received at a certain dosage rate for 1 hr, at a different dosage rate for 4 hr, etc., with intervals of no exposure in between. If such intermittent exposure continued indefinitely, it would be strictly correct to say that the exposure occurred at a "dosage rate" of a certain number of roentgens per day. However, this would have the implicit connotation that the exposure was continuous. To avoid possible confusion it has been customary heretofore to use the expression "daily dose." The same notation will be retained in this report, but 1 week instead of 1 day will be taken as the unit of time.

A permissible weekly dose is a dose of ionizing radiation accumulated in one week of such magnitude that, in the light of present knowledge, exposure at this weekly rate for an indefinite period of time, is not expected to cause appreciable bodily injury to a person at any time during his lifetime. One week as used here means any seven consecutive days,

not a calendar week. All clarifying remarks made in connection with the definition of permissible dose apply to the present case, also.

One week has been taken as the unit of time for practical reasons. When the exposure extends to a period of many years, variation of fractional doses and dosage rates occurring within one week may be assumed to be unimportant, especially when they are within the limits of radiological experience. Therefore, it shall be understood that a person may receive the permissible weekly doses stipulated for the critical organs, in one short or long exposure or in any sequence of exposures during the week. However, since little is known about the biological effects of radiation delivered in microsecond pulses of very high dosage rate, some allowance on the safe side should be made when the permissible weekly dose might be received in less than 1 sec.

4.5. Maximum Permissible Dose

In principle there is a maximum dose that just fulfills the requirements set forth in the definition of permissible dose. Any smaller dose, obviously, would also meet the requirements. Therefore, in protection rules or recommendations in which numerical values of permissible doses are given, the values are the highest ones permissible *under the stipulated conditions of exposure.* To bring this out explicitly they are called "maximum permissible doses." The same thing applies to permissible weekly doses.

4.6. Dose for an Organ

Utilization of the concept of critical organs requires specification of a maximum permissible dose for each critical organ under stated conditions of exposure. In general, the organ is not uniformly irradiated and therefore the tissue dose varies from point to point. When the variation is not large, an average tissue dose for the organ is satisfactory. The average can be obtained by determining the total energy absorbed by the organ and dividing by its mass. When the variation is large, an average dose for the region of the organ receiving the largest dose is more appropriate. Even with this extension, however, difficulties arise in the case of the skin and bloodforming organs, which are widely distributed. *For the skin the proper value is obviously the highest dose received by any skin area (of the order of a square centimeter).* For the bloodforming organs an average value of some sort is required. *An average dose for a significant*

volume of the bloodforming organs in the body region in which the tissue dose is highest is satisfactory. The "significant volume" may be assumed to be of the order of 1 cm.[3] *For the gonads the pertinent dose may be assumed to be the average dose in a significant volume of the organ in the region of highest tissue dose. The significant volume in this case may be taken to be 10 percent of the total volume of both gonads. For the lens, which is very small, the significant volume is the volume of the lens of either eye.* It should be noted that since the maximum permissible dose for an organ is an average dose in a significant volume of the organ in the body region in which the tissue dose is highest, some (small) portion of the organ is permitted to receive a higher tissue dose than the stipulated one. It should be noted, also, that a maximum permissible dose for an organ is associated with the conditions under which the exposure takes place. For example it will be seen later that the maximum permissible weekly dose for the skin recommended in this report is 600 mr when the whole body is exposed to penetrating X-rays and 1,500 mr when only the hands are exposed.

4.7. Specific Ionization in an Organ

The linear density of the ions along the path of an ionizing particle varies as the square of its charge and is a complicated function of its speed. Light and heavy particles can have the same specific ionization. However, in most cases of practical interest, dense ionization is associated with heavy particles (protons, deuterons, alpha particles, etc.). Therefore, large differences in specific ionizations occur in general between X-rays and beta rays on one hand and heavy-particle radiation on the other. In either case it is clear that one must deal with some average value of the specific ionization in a tissue. Since the biological effectiveness of X-rays and beta rays does not vary much even when the specific ionization varies from 10 to 100 ion pairs per micron,[6] it is convenient and justified for our purpose to ignore differences in specific ionization in this range. Therefore, it is unnecessary to determine the average specific ionization in an organ in the case of exposure to X-rays or beta rays.

When heavy ionizing particles are involved, the biological effectiveness of the radiation varies considerably with specific ionization in the range of 100 to 5,000 or more ion pairs per micron. Therefore, it is necessary and worthwhile to know what specific ionization to assign to the radiation

[6] At the end of the range of electrons the specific ionization is considerably higher than this, but in most practical cases this constitutes a small fraction of the total ionization.

traversing an organ,[7] in order to make a proper estimate of the biological effectiveness of a given tissue dose. If in this range the RBE were a linear function of the specific ionization, the average specific ionization would give the proper value of the RBE for the mixture. The relation between RBE and specific ionization is not linear; but because it is not known accurately and allowances must be made for this uncertainty anyway, the error introduced by using the arithmetical average of the specific ionization may be neglected. A more accurate procedure would be to subdivide the fraction of the dose involving high specific ionization and to determine the average for each subdivision. This presupposes that one is able to subdivide the dose into portions of different specific ionizations, which is not the case at present. Therefore, for purposes of protection it is acceptable to distinguish only between the portion of the dose due to light ionizing particles (X-rays, beta rays) and that due to heavy ionizing particles with specific ionization greater than 100 ion pairs per micron, and to estimate the average specific ionization for this portion. Actually at present there is no simple and direct way of determining the relative magnitudes of the two portions of the dose just mentioned and, therefore, approximations by indirect means must be made.

What has been said so far applies to the specific ionization at a given point in a tissue. In general, variations also occur from point to point in a critical organ. Again fine distinctions are unwarranted. *Therefore, it is recommended that the specific ionization to be used for the determination of the RBE for a critical organ be the maximum value of the average specific ionization just discussed obtaining in a significant volume of the critical organ receiving the highest dose.* It should be noted in this connection that present knowledge of specific ionization and RBE is only fragmentary. Very little attention has been paid to variations of average specific ionization with tissue depth when a large body is exposed to a beam of radiation. In general the specific ionization given in the literature is an estimated average for the beam of radiation as it enters the body. This adds to the difficulty of extrapolating results of animal experiments to man.

4.8. The Rem

It has been found convenient in practice to express doses of radiation of different specific ionizations in terms of a unit

[7] It is hardly necessary to point out that the specific ionization of interest is that obtaining in a given tissue and not that of the radiation beam in air before it enters the body.

that embodies both the magnitude of the dose and its biological effectiveness. The unit has been called the "rem" and in the past has been defined in terms of the rep and the RBE [dose in rems=(dose in reps)×RBE]. As already mentioned, the International Commission on Radiological Units has now recommended the rad as the unit of absorbed dose to replace the rep. However, it made no recommendation as to a unit corresponding to the rem.[8] Since the use of such a unit facilitates the reckoning of tissue doses of different specific ionizations, the International Commission on Radiological Protection, at its Copenhagen meeting in 1953, decided to continue to use the rem. However, the introduction of the rad to replace the rep necessitated a slight change in the magnitude of the rem (in the ratio of 93 to 100).

The difference between the rem as used now and as previously used is insignificant in its practical applications to the protection problem and, therefore, no changes in numerical values need be made in maximum permissible doses in use heretofore. At any rate, the numerical values given in the present report are in terms of the "new" rem based on the rad according to the following definition:

The rem is the quantity of any ionizing radiation such that the energy imparted to a biological system (cell, tissue, organ, or organism) per gram of living matter by the ionizing particles present in the region of interest, has the same biological effectiveness as an absorbed dose of 1 rad of X-radiation with average specific ionization of 100 ion pairs per micron of water in the same region.[9] Assigning for reference purposes, an RBE of 1 to X-rays with this specific ionization (lightly filtered 200-kv X-rays) we have in this case 1 rem=1 rad. For any radiation with a different specific ionization, the physical magnitude of a dose in rems may be obtained from the following relation:

$$\text{Dose in rems} = (\text{dose in rads}) \times \text{RBE}$$

or

$$\text{Dose in rads} = \frac{\text{dose in rems}}{\text{RBE}}$$

where RBE is the appropriate value of the biological effectiveness of the other radiation relative to that of X-rays with specific ionization of 100 ion pairs per micron, for the particular biological system and biological effect under

[8] The matter was not even discussed for lack of time.
[9] See comments in section 5.2.e, on calculation of average specific ionization.

consideration and for the conditions under which the radiation is administered.

It should be noted that because the RBE is influenced by a great many factors, strictly speaking, there is no such thing as exact equivalence of biological damage produced by X-rays and other radiations of markedly different specific ionization, in a biological system in which more than one effect takes place. In practice some particular effect is assumed to be paramount and the comparison is made on that basis. In the protection problem it is sufficient to consider the effects on the critical organs. Therefore, the RBE's of chief interest here are for certain potential effects on the critical organs under specified modes of exposure. The quantitative relationship between doses in rems and doses in rads will be given on this basis.

The choice of X-rays with specific ionization of 100 ion pairs per micron of water as a point of reference for the numerical values of the RBE, is an arbitrary one. The choice is justified, however, because this specific ionization applies to the range of X-ray voltages chiefly used in radiology in the past, during which time much of the background information on personnel exposure had its origin. It is fortunate that in this voltage range (30 to 200 kv) the specific ionization is essentially constant at about 100 ion pairs per micron of water, in round figures. The only disadvantage of this choice is that for X-rays of higher energy and in some other cases, the experimentally determined RBE may be less than one. This disadvantage does not appear in the protection problem, because it is satisfactory to assume that all X-rays and beta rays have an RBE of one, irrespective of their specific ionizations.

4.9. Tissue Dose

It has been pointed out already that when the entire body is exposed to penetrating radiation, some organs may be damaged or fail to function normally because some other organs may have been injured. Very little is known about indirect effects of this type, but it is probable that they do not play much of a part until the doses involved are so large that marked damage is produced in many organs. For protection purposes, therefore, it is satisfactory to assume that the potential damage to an organ depends almost entirely on the tissue dose received by the organ, under any given set of exposure conditions.

It has been pointed out, also, that the tissue dose should

be expressed in terms of energy absorbed, that is, in rads. However, in radiology, doses are generally expressed in roentgens and conversion to rads (or reps) is not always a simple matter. The complication arises from the fact that air and tissue do not have the same atomic composition and that tissues differ among themselves, the extreme example being fat and bone.

On the assumption that the average energy lost by an electron in producing an ion pair in air is independent of the energy of the electrons and amounts to 32.5 ev, 1 r of X-rays of any wavelength imparts 84 ergs of energy to the "associated corpuscular emission" [10] per gram of air, as kinetic energy available to ionize or "excite" atoms and molecules. If now the same X-rays pass through a tissue, the interaction of photons and atoms will be different because the atomic constituents of the two media are quite different; and the kinetic energy of the associated corpuscular emission per gram of tissue liberated by 1 r will be different. What is more important from the practical point of view, is that the difference varies with the wavelength of the radiation, and therefore there is no constant ratio between the two, even in the simplest case of a single tissue of definite composition.

When the radiation is in equilibrium with its associated corpuscular emission at the point of interest, the kinetic energy imparted to the "corpuscles" (secondary electrons) per gram of material is equal to the energy dissipated *in situ* per gram of material. Therefore, in this case, a dose of one roentgen represents an actual energy absorption of 84 ergs per gram of air at the point in question. In the case of tissue (or any other material) the same situation obtains, except that in general the energy absorption per gram of the material per roentgen will be different. It has been assumed heretofore that in the case of muscle and most soft tissues, ordinary X rays, when in equilibrium with the associated corpuscular emission, produce a local energy absorption of approximately 93 ergs per gram of tissue per roentgen. Through a combination of circumstances this quantity does not vary much with wavelength in the range of ordinary X rays (insofar as soft tissue is concerned). Therefore, 93 ergs per gram has been taken as the magnitude of the rep. By definition then, and under these special conditions, 1 r produces a (soft) tissue dose of 1 rep or 0.93 rad.[11] However, in general this is not true and in special cases the difference may be *very* large.

[10] See definition of the roentgen, section 2.18.

[11] The difference between 0.93 and 1 rad is insignificant in dosage differences relating to protection. Therefore, it may be assumed that 1 r of ordinary X-rays produces a soft-tissue dose of 1 rad.

In dealing with ordinary X-rays it is unnecessary to emphasize the equilibrium condition because the range of the secondary electrons is very short and the transfer of energy from the ionizing particles to solid matter occurs within a very short distance. In the case of multimillion-volt X-rays, however, the range in tissue of the ionizing particles (electrons and positrons) may be several centimeters long; and the situation is quite different. If the radiation is not in equilibrium with its corpuscular emission at the point under consideration, the relation between a dose in roentgens and the actual tissue dose in rads is indefinite. The large differences that may occur will be brought out best by an example. With X-rays produced at 70 million volts, a skin dose of 100 r[12] may produce a skin dose of 10 rads, when the X-ray beam is relatively free of the associated corpuscular emission before it strikes the skin. The beam would have to traverse several centimeters of tissue in order to acquire the full complement of associated corpuscular emission. Therefore, in this case the tissue dose *in rads* increases markedly with depth, whereas the tissue dose *in roentgens* decreases with depth. In a large mass of homogeneous soft tissue the dose in roentgens and the absorbed dose in rads become approximately numerically equal when the conditions are such that the X-rays are essentially in equilibrium with the corpuscular emission.

Because bone marrow is an important part of the blood-forming organs, it is well to consider the matter of tissue dose in this case. Because bone contains elements of higher atomic number than soft tissue, a given tissue dose in roentgens produces a numerically higher bone dose in rads. At the interface between bone and marrow the tissue dose in rads will be higher because of the presence of ionizing particles originating in bone in excess of those that would be produced in the marrow itself. This will occur when the quality of the radiation is such that the photoelectric effect in bone is considerable. In this case, however, the range of the photoelectrons is very short and the excess exists only in a very thin layer of marrow adjacent to bone.[13] For the bulk of the marrow the doses in rads would be nearly equal to the doses in roentgens. The situation is quite different in the case of multimillion-volt X-rays when the pair-production process in bone predominates. The ranges of

[12] The measurement of 70-Mv X-rays *in terms of the roentgen* is fraught with practical difficulties. This is irrelevant in the present case, because the hypothetical example is correct in principle.

[13] The biological significance of this effect is difficult to appraise, but is nevertheless included in the overall picture of exposure of radiologists. It cannot play an important part because when the photoelectric effect in bone is large the radiation is soft and relatively little reaches the bulk of the bone marrow in the body.

electrons and positrons produced in bone are then quite long and thereby much of the bone marrow would receive a numerically larger dose in rads than in roentgens. Because these X-rays are very penetrating this would apply to all bone marrow in the body.

From the foregoing discussion it is evident that the very large range of X-ray energies available today does away with the approximate generalization used heretofore that in the case of soft tissue "1 rad (or 1 rep) equals 1 r." A certain dose in roentgens may produce in soft tissue a much lower or a considerably higher dose in rads (numerically) depending on circumstances. While it is obviously more significant to express tissue doses in rads, in general it is not a simple matter to do so. It is possible at present to measure with good accuracy tissue doses in rads for all kinds of ionizing radiation, but very little experimental information is available.

4.10. Determination of Tissue Doses and Accuracy

Measurements of air doses or tissue doses in roentgens shall be made under the conditions existing in the region of interest and in accordance with the requirements of the definition of the roentgen.

Measurements of tissue doses in rads shall be made under the conditions existing in the region of interest, with instruments that permit the evaluation of the energy imparted to the tissue in question by the ionizing particles of the radiation.

Because it is not always practicable to make such measurements, tissue doses in rads may be determined indirectly. In such cases the methods and constants used shall be those generally accepted by experts in this field at the time of interest.

The accuracy of measurements or indirect determinations of tissue doses shall be as high as accepted practice permits at the time of interest. At any rate, proper allowances for possible errors shall be made to make sure that the actual doses to be received by a person cannot exceed the maximum permissible limits.

5. Basic Permissible Weekly Doses for the Critical Organs

5.1. Long-Term Exposure to X-rays

a. Whole-Body Exposure under the Conditions of Radiological Practice

Pertinent radiological experience is based largely on whole-body exposure of personnel to the X-rays used in diagnosis and therapy (up to 200 kv). The spatial distribution of radiation in the body under these conditions can be very different but nevertheless it follows certain patterns. For instance the skin, or a more or less superficial layer of tissue,[14] always receives the highest dose, *in roentgens*, and certain deep-seated tissues the lowest. The bloodforming organs, being widely distributed, receive intermediate average doses.

Figure 1 shows the depth distribution of radiation in the main portion of the body resulting from exposure to X-rays of different qualities under the following conditions: A single nearly parallel beam of radiation (i. e., long target-to-skin distance) perpendicular to the body axis; large field; stationary body. These are essentially the basic conditions of whole-body exposure in a radiological department, for persons who stay outside of the X-ray rooms. In general the person is not stationary with respect to the beam and the radiation may reach his body from different directions at different times, or he may be exposed to X-rays from a number of X-ray machines. In these cases the distribution of radiation in the body is more nearly uniform than is indicated by the curves of figure 1.

For the purpose at hand the main point is that when a permissible dose is specified in terms of air dose in roentgens, as heretofore, the tissue doses in roentgens at all depths less than 5 cm are numerically larger than the air dose, under the conditions of radiological practice, excluding fluoroscopy.[15] The tissue depth for which this is true may be as large as 10 cm depending on the quality of the radiation. For purposes of calculation it may be assumed that the average depth of the bloodforming organs is 5 cm. Therefore, with a permissible air dose of 100 mr/day the (implied) permissible dose for the bloodforming organs has been in the past greater

[14] With 200-kv X-rays the tissue dose is not highest at the surface but at some depth within the first 2 cm. The difference, however, is negligible for the present purpose.

[15] In the case of fluoroscopy the target-to-skin distance may be short and the half-value layer less than 0.2 mm of copper. (It is assumed that the HVL of the radiation outside of protected X-ray rooms is greater than this.)

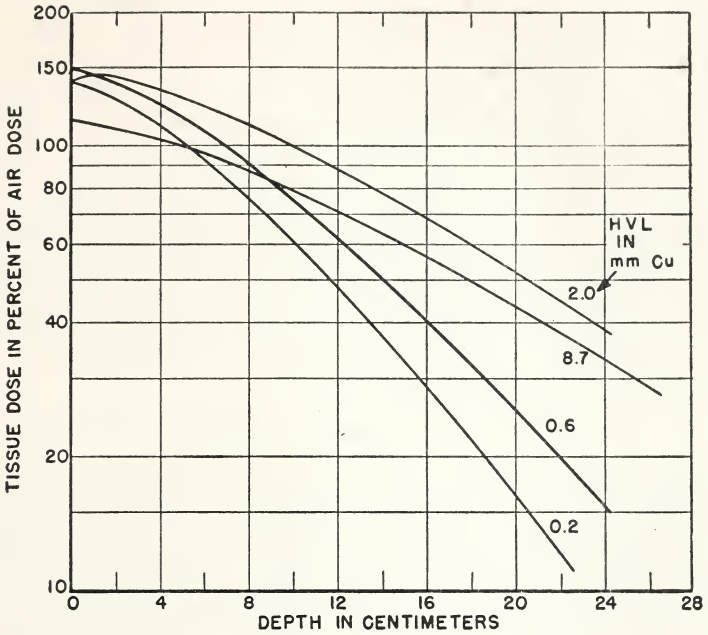

FIGURE 1. *X-ray dose distribution in the main portion of the body.*

Irradiation conditions: Stationary body; one large parallel beam perpendicular to body axis; different qualities of radiation as indicated by half-value layers (HVL) in millimeters of copper shown on curves.

than 100 mr/day. On the basis of a 5.5-day week this corresponds to a weekly dose of more than 550 mr in the bloodforming organs.

b. Bloodforming Organs

It is now recommended that for exposure of the whole body to X-rays for an indefinite period of years, the basic permissible weekly dose in the bloodforming organs be 300 mr. This is not a maximum permissible weekly dose for the bloodforming organs, but one that will serve as a basis in the formulation of maximum permissible limits of exposure under the different conditions of exposure of practical interest.

It is well to state explicitly that the recommended reduction in the permissible dose for the bloodforming organs is not based on definite knowledge that 0.1 r/day measured in air is too high. There is actually no direct information indicating that 0.1 r/day is too high. Because the seriousness of radiation hazard was generally realized 20 or 25 years ago,

protective measures of varying efficacy have been used and gross over-exposure has been avoided. Some radiologists and technicians have been exposed at a considerably higher rate than 0.1 r/day and some at a lower rate. The general impression among radiologists is that no harmful effects result from whole-body exposure at these levels (i. e., in the neighborhood of 0.1 r/day). Nevertheless, in the absence of long-term experience backed by valid statistical data, it is desirable to be on the safe side. An additional reason is furnished by the results of pertinent animal experiments, which indicate that the factor of safety involved in whole-body exposure at the rate of 0.1 r/day is not so large as it was thought to be at the time that this permissible level of exposure was recommended.

c. Skin

Human skin is quite radiosensitive but recovery is rapid; therefore, when the exposure extends over a long period of time, a much larger total dose is required to produce a given effect. Because cancer of the skin is generally readily curable and leukemia is always fatal, the danger of over-exposure of the bloodforming organs is inherently much more serious. On this basis the permissible dose for the skin could be much larger than for the bloodforming organs. The criterion adopted here, however, is much more stringent in that the aim is to prevent the development of cancer in either case. On this basis it is not wise to make the permissible dose for the skin much higher than that for the bloodforming organs. A factor of two is definitely on the safe side. *Accordingly it is recommended that for exposure of the whole body to X-rays for an indefinite period of years, the basic permissible weekly dose in the skin be 600 mr.* Again this is not a maximum permissible limit for the skin dose, because under special conditions higher weekly skin-dose limits will be recommended later.

In the case of whole-body exposure to ordinary and supervoltage X-rays there is an indirect advantage in making the permissible skin dose not too different from that of the bloodforming organs, in that the doses received by tissues at intermediate depths cannot be much larger than the bloodforming-organs dose. This is not important in the case of local exposure of small parts of the body or when the radiation is of such low penetrating power that it is almost completely absorbed within a few millimeters of tissue.

It has been mentioned previously that the cells in the basal layer of the epidermis are the ones to be protected. Therefore, the tissue dose of interest here is the one obtaining in this layer. For the purposes of this report it may be assumed that the cells in the basal layer of the epidermis are located at a depth corresponding to 7 mg/cm^2, for the skin of the major portions of the body. For the skin in some parts of the body, notably the palms of the hands of manual workers, the depth is considerably greater and suitable allowances may be made for absorption by the larger thickness of "inert" tissue, provided that the dose in other skin areas does not exceed the pertinent permissible dose.

d. Gonads

When genetic changes manifestable in future generations are excluded, the radiosensitivity of the gonads, with respect to sterility or impairment of fertility, may be taken to be essentially the same as that of the bloodforming organs. *Therefore, it is recommended that for exposure to X-rays for an indefinite period of years, the basic permissible weekly dose in the gonads be 300 mr.* This recommendation is based solely on considerations involving avoidance of damage to the exposed individual himself. It should be realized that any amount of radiation received by the gonads of even a few individuals before the end of their reproductive period is likely to add to the number of undesirable genes present in the population. While the great majority of these genes might have no recognizable effects for a considerable number of generations, all are potentially bound to result eventually in undesirable conditions. The effects are ordinarily so remote, however, that the traceable descendants of the exposed individuals would not be appreciably more affected than others in the general population.

In adults the ovaries are situated at a greater depth than 5 cm from the nearest skin surface. The average depth may be assumed to be 7 cm. In general, however, the exact depth is immaterial as long as it is more than 5 cm; because, with a permissible weekly dose of 300 mr for the bloodforming organs (assumed to be at an average depth of 5 cm), the weekly dose at any greater depth will be equal to or less than 300 mr, according to the basic dose distribution (see below).

In men the minimum tissue depth for the gonads is small, but in general they are shielded by considerable thickness of tissue. An average tissue depth in this case is practically meaningless. When the testes are *directly* exposed to penetrating radiation the depth dose distribution is practically

uniform and the depth chosen makes little difference. When the radiation is very soft it is appropriate to take an average of the dose in a significant volume of the testes in the region receiving the largest dose. The "significant volume" in this case may be assumed to be 10 percent of the total volume of both testes, and the average depth to be 1 cm. When the radiation reaches the person from widely different directions, considerable shielding of the testes occurs and suitable allowances therefor may be made. Similarly some allowance may be made when the person normally moves around with respect to the general direction of the radiation.

e. Lens of the Eye

As stated previously, radiological experience does not indicate that the lens of the eye is particularly sensitive to X-rays, with respect to cataract formation, but it must be considered as a critical tissue because of its high sensitivity to fast neutrons. To be on the safe side it will be assumed that the radiosensitivity of the lens of the eye to X-rays is the same as that of the bloodforming organs. *Therefore, it is recommended that for exposure to X-rays for an indefinite period of years, the basic permissible weekly dose for the lens of the eye be 300 mr.*

It is important to note that this constitutes a considerable reduction in the permissible dose for the lens of the eye. On the basis of a permissible daily dose of 100 mr measured in air, the dose in the lens would be substantially higher than 100 mr—perhaps 150 mr—because of backscatter and the small tissue depth involved. Advantage will be taken of this fact in specifying the permissible dose for exposure to radiation of high specific ionization. The average depth of the lens of the eye may be assumed to be 3 mm.

f. Other Organs and Tissues

It will be seen that making the permissible skin dose twice that of the bloodforming organs introduces certain complications in the stipulation of permissible doses for other tissues. In general the tissue dose *in roentgens* decreases gradually with increasing tissue depth. If the conditions of exposure are such that the dose at 5 cm depth (the assumed average depth of the bloodforming organs) is less than 50 percent of the skin dose, the permissible dose for the skin sets the limit. On the other hand if the depth dose at 5 cm is greater than 50 percent of the skin dose, the permissible dose for the bloodforming organs sets the limit. In either case the tissues between the surface of the skin and a depth of 5 cm may

receive weekly doses between 300 mr and 600 mr.[16] This, however, is not too different from the dose distribution occurring in occupational exposure in radiological practice and, therefore, may be assumed to be satisfactory. On the other hand, exposure to other types of radiation under certain conditions may produce an absorbed dose distribution with a high peak within the first 5 cm of tissue or at greater depths. It becomes necessary, therefore, to limit in some way the dose that these tissues may receive. For the sake of definiteness it is well to adopt as a guide a spatial distribution of radiation in the main portion of the body that conforms with the permissible doses for the critical organs and at the same time does not depart too far from the distributions produced by whole-body exposure in radiological practice. Because the beam or beams of radiation can have any orientation with respect to the body, the distribution of interest is one in which the depth doses apply to peripheral layers of tissue from the surface of the body inward. *The spatial distribution of radiation shown in figure 2 conforms with the present requirements and is recommended as an arbitrary standard for the purposes of this report.*

It is important to note that the curve of figure 2 sets the *limits* for the weekly tissue doses at different depths from the body surface (in any orientation) when the weekly tissue dose at 5 cm depth is 300 mr. Thus, the weekly tissue dose at 2 cm depth should not exceed 500 mr and that at any depth greater than 5 cm should not exceed 300 mr. Obviously, such a distribution of radiation cannot be obtained in practice by exposure to X-rays. However, as long as (1) weekly doses are expressed in *roentgens*, (2) the weekly tissue dose at the surface is not more than 600 mr, and (3) the weekly tissue dose at 5 cm depth is not more than 300 mr, the weekly tissue doses in any tissue within the trunk of the body will not exceed the appropriate values given by the curve of figure 2, no matter how whole-body exposure to X-rays from external sources takes place. Accordingly, the curve of figure 2 is not essential to the stipulation of permissible weekly doses in *roentgens* in the case of X-rays. The need arises when tissue doses are expressed in rads, because then great variations in depth doses may occur even in the case of exposure to X-rays and more so for other types of radiation. For this reason, it is further stipulated that the spatial distribution of radiation of figure 2 be assumed to represent the basic permissible weekly tissue doses from the

[16] Tissues beyond the 5-cm depth receive 300 mr/week or less, which is less than the permissible weekly dose for the most critical organ and, therefore, satisfactory.

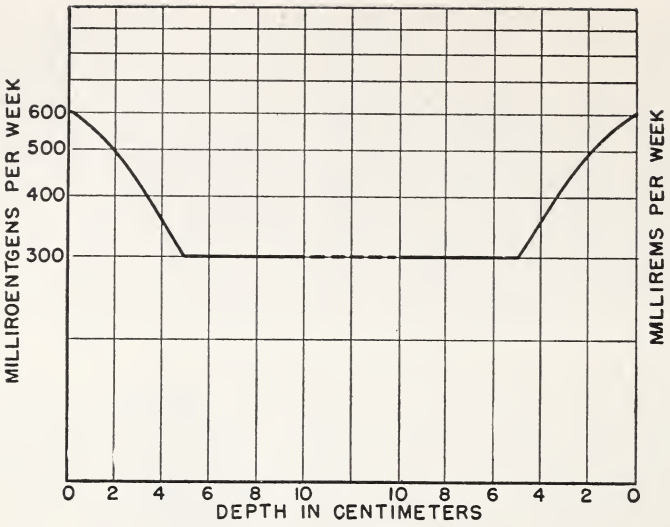

FIGURE 2. *Basic permissible dose distribution in the main portion of the body.*

Basic permissible weekly dose is (a) 600 mr for the skin, (b) 300 mr for the bloodforming organs at an assumed average depth of 5 cm, and (c) according to the curve for tissues at other depths from the surface of the main portion of the body. The basic permissible dose distribution remains the same when the permissible doses are expressed in rems.

surface of the main portion of the body in terms of rads as well as roentgens, *in the case of whole-body exposure to X-rays. For other types of radiation and in general the spatial distribution of radiation of figure 2 represents the basic permissible weekly tissue doses in rems at different depths from the surface of the main portion of the body.* (See below.) For future reference this will be called the basic permissible dose distribution, or simply the basic dose distribution.

5.2. Long-Term Exposure to Other Types of Radiation

a. General Approach

The permissible weekly X-ray doses for the critical organs recommended above, are considered to conform with the concept of "permissible weekly dose" established earlier in this report. This can be done with confidence in the case of X-rays because of abundant radiological experience. In the case of other types of radiation no such background information is available and it is necessary to make estimates based largely on animal experiments and observations made on the survivors of Hiroshima and Nagasaki. Accordingly a more cautious approach is indicated. At the same time

it is not desirable to make the permissible weekly doses so low as to be impractical. Obviously the potential risk of exposure to any type of ionizing radiation *should not be greater* than that involved in exposure to ordinary X-rays under comparable conditions. It is, therefore, necessary to choose permissible weekly doses that comply with this requirement and at the same time do not involve impractically large factors of safety. Formally this purpose is accomplished as follows:

Based on past experience with ordinary X-rays, certain basic permissible weekly tissue doses *in roentgens* are assigned to the critical organs (and body tissues at different depths according to the adopted basic dose distribution). In order to comply with the requirement that the potential risk of exposure to any type of radiation should not be greater than that involved in exposure to ordinary X-rays under comparable conditions, it is necessary that the potential injury to the critical organs and other body tissues be no greater than in the case of X-ray exposure at the respective permissible weekly tissue doses. This involves the biological effectiveness of the radiation relative to that of ordinary X-rays (RBE) for each critical organ and pertinent effect. Since RBE's are determined on the basis of absorbed dose, it is necessary to assign to the critical organs, etc., basic permissible weekly tissue doses in rads resulting from exposure to ordinary X-rays at basic permissible weekly tissue doses in roentgens. It is satisfactory for this purpose to stipulate that for ordinary X-rays the basic permissible weekly tissue dose in rads for a given critical organ shall be numerically equal to the value in roentgens assigned to it. Since the RBE for ordinary X-rays has been taken as one, the basic permissible weekly tissue dose in rems for a given critical organ is in this case numerically equal to the value in rads (and the value in roentgens) assigned to it.

b. Permissible Weekly Doses in Rems

Accordingly, the basic permissible weekly tissue doses for exposure to any ionizing radiation for an indefinite period of years, shall be as follows:

Skin: 600 millirems
Bloodforming organs: 300 millirems
Gonads: 300 millirems
Lens of the eye: 300 millirems
Other organs and tissues of the body according to the basic dose distribution given in figure 2.

These are tissue doses in a significant volume [17] of the organ in question in accordance with section 4.6.

In practice it is necessary to translate a permissible dose in rems to one in rads under the exposure conditions of interest. This is accomplished by means of the relation, Dose in rads=(Dose in rems)/RBE, using the appropriate value of RBE. It is obvious that fulfillment of the requirement that the potential risk of exposure to any type of radiation should not be greater than that involved in exposure to ordinary X-rays under comparable conditions depends on the choice of the appropriate RBE values. It is desirable, therefore, to discuss this subject somewhat in detail.

Because it is known that the biological effects of all ionizing radiations are the same *in kind,* the critical-organs criterion is also valid in the case under consideration; but relative differences in degree of effect must be taken into account. The problem is to choose the value of the RBE for each critical organ (irradiated under specified conditions) that, in the light of present knowledge, may be expected to meet the above-mentioned requirement. It has been pointed out already that the RBE varies with numerous factors, and, therefore, it is not possible to assign to it a single value determined only by the specific ionization of the radiation. For the purpose at hand the following procedure will be used. The kind of exposure of most practical importance is the one in which the entire body is irradiated more or less uniformly, intermittently, and at a substantially constant rate, over a period of many years. Present knowledge indicates that under these conditions the bloodforming organs, the gonads, and the lens of the eye are the most radiosensitive tissues. Therefore, these are the important critical organs. (The skin still constitutes a critical organ.) In principle there is one RBE for the degree and kind of effect of interest here in each critical organ exposed to radiation of a given specific ionization under the stipulated conditions. However, at present RBE's are not known with sufficient accuracy to warrant distinction. Therefore, it is satisfactory for the purposes of this report to choose for a given specific ionization one RBE for all critical organs such that the risk of damage in any one of them is no greater than it is in the case of exposure to X-rays under comparable conditions.

When the whole body is exposed to penetrating radiation all organs may receive essentially the same tissue dose and therefore the applicable RBE is the one for the most critical

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[17] Area and depth, for the skin.

organ and effect, under the stipulated conditions of exposure. In the case of radioactive substances within the body the proper value of the RBE is the one that applies to the pertinent critical organ and effect.

c. RBE for Fast Neutrons

In the past, irradiation of the whole body by external sources with radiation of high specific ionization has been possible only by exposure to fast neutrons. In such cases the specific ionization [18] of the protons set in motion by the neutrons has been estimated to be roughly 10 times higher than that of the secondary electrons produced by ordinary X-rays. Experiments in which laboratory mammals have been chronically exposed to fast neutrons (produced by cyclotrons or uranium fission) show that the RBE for the bloodforming organs—based on periodic blood counts—is less than five. There is some evidence that the RBE for the gonads with respect to sterility or impairment of fertility and for the lens of the eye with respect to cataracts, is higher than five. Therefore, an RBE of ten is recommended for these critical organs when the whole body is chronically exposed to fast neutrons similar (in energy spectrum) to those used heretofore in pertinent animal experiments. (RBE's in terms of specific ionization are given in the following section.)

Further justification of the choice of an RBE of ten in this case is necessary because the subject at present is highly controversial. The greatest divergence of opinion occurs in the case of cataracts. The situation is as follows. The latent period for cataract manifestation is long. Therefore, in experiments in which animals have been chronically exposed at rather low levels of radiation, cataracts have appeared at the time when many of the control and irradiated animals had died; and the survivors were not in sufficiently large numbers to yield statistically significant results. For this reason, for instance, large variations in the percentage of cataracts produced have occurred among separate groups of mice irradiated under the same conditions. One might then take the point of view that the RBE for cataract formation should be based on the group that yielded the largest percentage of cataracts.

An important point to remember is that in such experiments the exposure level is adjusted to produce marked effects. For protection purposes, however, one is dealing

[18] Specific ionization in this report always means average specific ionization.

with levels of exposure at which there is either no injury at all or the effect is minimal, in the light of the definition of a permissible dose. Whether an RBE determined on the basis of marked injury is applicable to the protection problem is questionable. The point of chief concern in the case under discussion is really whether the RBE is apt to be larger when long-term exposure takes place in the range of permissible levels. This is a typical case of differential variations discussed earlier. Available experimental evidence indicates that the RBE for cataract formation is higher when the weekly dose is lower and the time of exposure longer. The phenomenon may be explained on the assumption that the rate of recovery is higher in the case of X-rays than it is in the case of fast neutrons. In these experiments, however, the exposure level has been much higher than that which would be considered permissible and extrapolation to the latter level is again questionable. Obviously, if any recovery at all takes place there must be a level of exposure—however low—that would not produce cataracts at all. At such levels, then, the RBE would be meaningless, since neither X-rays nor fast neutrons would produce cataracts.

Another important point is involved in the problem under discussion. The study of radiation-induced cataracts is being pursued vigorously; more delicate techniques are being used; and cataractous changes are being observed earlier and for smaller doses. At some point it will be necessary to decide what persistent cataractous changes may lead to appreciable injury of the lens during the lifetime of the individual, within the meaning of permissible dose.

Finally it should be noted that the RBE sets the permissible dose of fast neutrons for the lens of the eye *with respect to the corresponding permissible tissue dose for X-rays.* As already pointed out, practical experience shows that the lens of the eye in humans is more radioresistant than the bloodforming organs in the case of continued all-body exposure to X-rays. Nevertheless, the recommended permissible weekly dose of X-rays for the lens is the same as for the bloodforming organs. Therefore, the additional factor of safety embodied in the permissible X-ray dose for the lens, is also included in the derived permissible fast-neutron dose. This is tantamount to the direct recommendation of a substantially larger RBE for the lens of the eye in the corresponding case of fast neutrons.

d. RBE for Radiation of Higher Specific Ionization

The newer tools of nuclear physics have greatly extended the range of specific ionizations of interest in the protection problem. It becomes necessary, therefore, to assign values of the RBE for the critical organs according to the magnitude of the specific ionization. Going first to higher specific ionization than that of protons, it may be pointed out that direct experimental data on mammals are not available at present. Work with alpha particles of radioactive substances provides some leads. There is also evidence that the RBE does not increase indefinitely as the specific ionization increases;[19] it tends to level off or perhaps decrease beyond the value for ordinary alpha particles. It is the consensus at this time that for protection from external radiation an RBE of 20 is ample when the specific ionization is in the range of that generally associated with the alpha particles of radioactive substances. Because knowledge in this field is very limited, it is not practical to distinguish specific ionizations that differ by less than a factor of two or three. Therefore, in table 3 are given the recommended values of RBE for certain ranges of specific ionization.

e. Comments on RBE for X-rays and Beta Rays

The average specific ionization of the secondary electrons of X-rays produced at voltages of 30 to 200 kv is essentially constant. One hundred ion pairs per micron of water is a good round figure for this voltage range, although the value for 200-kv X-rays as ordinarily used in therapy (i. e., with substantial filtration) is approximately 80 ion pairs per micron of water.[20] For voltages lower than 30 kv the specific ionization increases considerably, but on the other hand the penetration of the X-rays becomes so low that the dose in the bloodforming organs is no longer the limiting factor. In view of the fact that the permissible limits of exposure for the skin already include a considerable factor of safety, it is unnecessary to take into account the greater RBE of such radiation. For X-rays produced at voltages higher than 200 kv, the average specific ionization is less than 100 ion pairs per micron and the RBE is known to be less than one. From the foregoing it follows that adopting

[19] It should be noted that the biological effects under consideration here are "gross" or overall effects on mammals. It is well known that for some effects, especially those involving damage in a very small entity such as a gene, the RBE of alpha particles is equal to or less than one, relative to that for 200-kv X-rays.

[20] It is obvious that the actual value depends on the tissue depth, because scattered X-rays are of lower energy.

TABLE 3. *Recommended values of the relative biological effectiveness (RBE) of radiation of different specific ionizations applicable to exposure to radiation from external sources* [a]

Present knowledge of the biological effectiveness of radiation of different specific ionizations does not warrant fine distinctions. Therefore, ranges rather than individual figures are given in this table. For any range of specific ionization it is safer to use the higher of the two values of RBE given for that range, but a value obtained by linear interpolation is acceptable.

X-rays, electrons, and positrons of any specific ionization: RBE=1		
Heavy ionizing particles		
Average specific ionization [b] (ion pairs per micron of water)	RBE [c]	Average linear energy transfer (LET) to water [d] (kev per micron of water)
100 or less	1	3.5 or less.
100 to 200	1 to 2	3.5 to 7.0.
200 to 650	2 to 5	7.0 to 23.
650 to 1,500	5 to 10	23 to 53.
1,500 to 5,000	10 to 20	53 to 175.

[a] The critical organs and effects considered are: skin with respect to cancer, bloodforming organs with respect to leukemia, gonads with respect to impairment of fertility, and lenses of the eyes with respect to cataracts.

[b] Specific ionization is expressed in ion pairs per micron of water in terms of its air equivalent.

[c] RBE is in terms of the pertinent biological effectiveness of ordinary X-rays for which the average specific ionization in the tissue of interest is assumed to be 100 ion pairs per micron of water. Permissible dose in rads=(permissible dose in rems)/RBE.

[d] Linear energy transfer is given in kev per micron of water, using 35 ev per ion pair.

an RBE of one for all qualities of X-rays is on the safe side insofar as most body organs are concerned. In the case of the skin—for which this is not true—the difference in RBE for very low voltage X-rays may be neglected. Accordingly for the purposes of this report, the RBE for X-rays and gamma rays of any photon energy shall be considered to be one, provided the transfer of energy to the tissues takes place through electrons and/or positrons, as essentially the sole ionizing particles associated with or present in the radiation. Obviously, the same reasoning leads to the acceptance of an RBE of one for beta rays.

The average specific ionization of 80 (or 100) ion pairs per micron of water for 200-kv X-rays is *the value generally quoted in the literature.* D. V. Cormack and H. E. Johns [Brit. J. Radiol. XXV, 369 (1952)] have pointed out that the value obtained depends on the method of calculation. For 200-kv X-rays they obtained a "mean ion density" of 55 ion pairs per micron of water by dividing the total number of ion pairs per cubic centimeter by the total range (in

microns) of the secondary electrons produced per cubic centimeter. They also calculated an "average ion density" of 102 ion pairs per micron for the same X-rays, based on a mean initial energy of 14 kev for the secondary electrons liberated in water. This value agrees with the value used in the present report, but the authors point out that the lower value is the one that should be used. It is obvious that when the matter is finally settled the numerical value of the specific ionization of 200-kv X-rays may be found to be quite different from the one of 80 to 100 used in this Handbook. For this reason it would be better at this time not to use specific ionization (or LET) in numerical terms as the basis for the RBE values given in table 3. On the other hand, it is no longer possible to assign RBE values to "protons," "alpha particles," etc., because at the very high energies now available, the specific ionizations of these particles approach those of electrons. The uncertainty as to the true value of the specific ionization is greatest in the ordinary X-ray region. Fortunately in this region there is little change in specific ionization, no matter how it is calculated, and experiments have shown that there is little change in RBE. This is the reason for the assignment in this report of an RBE of one to electrons, positrons, and X-rays of any energy. This "lumping process" will not be changed by any new determinations of specific ionization, although it may be changed by the accumulation of better knowledge of the *biological* effects of radiation. The calculation of "average" or "mean" specific ionization of heavy particles is simpler and the numerical values are not expected to be materially changed in the future.

It may be well to point out that at this time there is no general agreement on the point of reference for the RBE. In radiobiology, where it is of interest to study small variations in RBE, it seems preferable to assign a value of one to the RBE for the gamma rays of radium, for which the specific ionization in small biological objects (about 7 ion pairs per micron) is close to the theoretical minimum (5.7) for a singly charged ionizing particle. For protection purposes, where small differences in RBE occurring in the useful range of X-ray energies are generally neglected, it is preferable to set the RBE equal to one for an average specific ionization of 100 ion pairs per micron. This, as we have just seen, is a representative value for the wide range of X-ray voltages largely employed in radiology and radiobiology and as calculated heretofore.

The difference in point of reference is inconsequential as long as the RBE for any specific ionization less than 100 ion

pairs per micron is assumed to be one. However, in the literature RBE's are often given in terms of the RBE for radium gamma rays and an RBE of 1.5 is then assigned to ordinary X-rays. In comparing the values recommended here with those quoted in the literature the appropriate correction should be made if the point of reference is not the same. It will be seen, for instance, that the RBE of 10 recommended to apply to fast neutrons with specific ionization of 650 to 1500 ion pairs per micron, corresponds to an RBE of 15 on the basis of an RBE of one for radium gamma rays (that is, when the difference in RBE between ordinary X-rays and radium gamma rays is not neglected). Therefore an RBE of ten on the basis of an RBE of one for ordinary X-rays is substantially more conservative than an RBE of 10 based on an RBE of one for radium gamma rays.

f. Mixed Radiation

In practice, heavy-particle radiation with high specific ionization is generally "contaminated" with radiation of low specific ionization (i. e., X-rays, electrons, positrons). Or, the occupation is such that the individual is exposed simultaneously or successively to different types of radiation of widely different specific ionization. This problem was touched on indirectly in the discussion of "specific ionization in an organ" (section 4.7) and the general procedure was outlined. It will be recalled that the important point is to appraise separately the relative contributions to a tissue dose made by ionizing particles with specific ionization less than and higher than 100 ion pairs per micron. One then estimates the average specific ionization for the heavy-ionizing-particle component and chooses the appropriate value of the RBE to convert that portion of the dose into rems. The following hypothetical example will illustrate the procedure.

In one week a person was exposed separately to high-energy X-rays and to fast neutrons. Let us assume that during this time he received a dose of 80 millirads (in the pertinent critical tissue) while he worked with X-rays and a dose of 20 millirads while he worked with fast neutrons. Let us assume further that in the exposure to neutrons 50 percent of the dose was contributed by ionizing particles with specific ionization less than 100 ion pairs per micron and 50 percent by particles with an average specific ionization of 1,000 ion pairs per micron for the organ in question. This means that the dose for the week consisted of 90 millirads of radiation for which the RBE is 1 and 10 millirads of radiation

for which the RBE is 10. Therefore, the total dose was $(90\times1)+(10\times10)=190$ millirems. This example serves to emphasize the importance of estimating wisely the contribution to the dose made by ionizing particles of high specific ionization. This contribution was only 10 percent of the total dose in rads but it is more than 50 percent of the total dose in rems.

g. Internal and External Sources

In cases in which a person has radioactive material in the body, the critical organs may receive appreciable doses from these internal sources. The exposure in such cases is more or less continuous and account must be taken of this fact. There are problems of general distribution of the material in the body, local macro- and microconcentrations, rate of elimination, etc., that complicate the determination of the dose received by an organ. These are outside the domain of this subcommittee, but appropriate recommendations have been made by the Subcommittee on Permissible Internal Dose. (See National Bureau of Standards Handbook 52.) Assuming that the tissue dose in rems in the pertinent critical organ, resulting from internal sources, has been determined in the approved way; exposure of the individual to radiation from external sources shall not cause the organ dose to exceed the appropriate maximum permissible weekly dose in rems for that organ and the conditions of exposure.

6. Modifying Factors in Long-Term Exposure

6.1. Age

Because this report deals primarily with the protection of persons occupationally exposed to radiation, only adult men and women are directly involved. It may be assumed that the over-all radiosensitivity of adults remains essentially the same throughout life. Organ radiosensitivity with respect to some effects becomes obviously meaningless in one special case after a certain age. That is, women who have passed the menopause can have no children and therefore, the hazard of becoming sterile no longer exists. In man, sterility in later life is generally inconsequential. A similar situation exists with regard to genetic injury transmittable to future generations, in which case the important thing is the dose received up to the time of conception of a particular child. In effect, the gonads cease to be critical organs beyond the reproductive age. The distinction may be made at age 45,

which in most cases is the upper limit of the reproductive period. For other reasons the difference in permissible doses for the two age groups cannot be large, but a factor of two is reasonable.

It has been pointed out that when a single dose is given by a short single exposure the latent period for the manifestation of injury is longer the smaller the dose. For most "gross" effects of radiation a (single) dose of a certain magnitude is required before an effect of a perceptible degree is produced. In such cases if the dose is below this threshold value no perceptible effect is produced at any time; one might say that the latent period is infinite.

When the dose is spread over a *long* period of time the latent period is much longer for two main reasons: (1) the dose required to produce a certain degree of effect is larger because of the process of recovery, and (2) the time required to administer this dose is long. Hence, if the dosage rate (weekly dose) is low enough, the latent period may be made longer than the lifespan. The dosage rate that is just low enough to accomplish this may be called the threshold dosage rate.

There are in principle different threshold doses and threshold dosage rates for the different tissues and organs of the body and all different effects that may be produced. A conspicuous exception is the induction of gene mutations previously pointed out. There may be other exceptions that are not known today and in some cases the rate of recovery may be so small that the threshold dosage rate must be very low. It is important to note that when a tissue is irradiated with a threshold dosage rate, as defined above, recovery is not quite sufficient to overcome the effect of the radiation. Theoretically in a time longer than the lifespan, the effect would become apparent. From this it follows that the magnitude of the permissible weekly dose should increase with the age at which the exposure starts. Obviously, a person starting at age 45 will receive a lower total dose in the normal span of life than one starting at age 20, when the exposure is at the same weekly rate and all other conditions are the same. Also, the latent period for exposure received later in life extends beyond the lifespan. However, it is not practical to assign increasing values to the permissible weekly dose according to the age at which the exposure starts.

As already stated in the case of the gonads the permissible weekly doses can very well be doubled after age 45. As regards the other critical organs and the effects envisaged, a

factor of two after age 45 does not alter the situation materially, especially since—as far as is known today—the recommended weekly doses are well below the theoretical threshold dosage rates defined above. Furthermore, if the maximum permissible weekly doses for persons over 45 are twice the basic permissible weekly doses, there is still a net gain on the side of safety over the heretofore accepted maximum permissible limit of 0.1 r/day for all adults. Recommendations to this effect, with special qualifications, are made below in the Protection Rules, section 8.

6.2. Weekly Dose Fluctuations

To be on the safe side it is well to assume that the long-term dosage rate represented by the basic permissible weekly dose is not much lower than the threshold dosage rate discussed above. If for a time the weekly dose substantially exceeds the permissible value, the relation between biological effect and recovery is altered unfavorably. The opposite is true when the weekly dose is materially less than the permissible weekly dose. Whether for equal total doses accumulated over a given period of time the two alterations balance out is difficult to predict, because very little is known about the mechanisms of the radiation stimulus and the recovery process. The matter hinges largely on whether with a dosage rate severalfold higher than the basic permissible weekly dose, applied for a relatively short time, the threshold dose for possible irreversible changes (other than genetic) is exceeded; in which case a subsequent period of exposure at a rate lower than the basic permissible weekly dose cannot undo the damage. With very high weekly doses it is obvious that damage can be done that cannot be obliterated by a subsequent period of no exposure at all. In the range of permissible weekly doses, however, one is dealing with minimal changes; and it is reasonable to suppose that some compensation takes place. However, it is obvious that, because the permissible dosage rate is very small, the compensatory effect of even a long period of nonexposure cannot be much. If irreversible effects with no threshold are involved (as in the case of gene mutations) the time distribution of the dose is of no importance and the effect of a given dose of radiation is independent of the dosage rate. It is probable that both mechanisms are involved to some extent. Hence, it is desirable to avoid temporary exposures at high weekly doses.

The problem of practical interest is how far the weekly dose may be allowed to fluctuate from an average value

represented by the basic permissible weekly dose without increasing the risk. It will be recalled that the concept of a weekly dose envisages and permits marked variations of dosage rates and fractional doses during the week. However, further extension of the period during which this averaging process is allowed will introduce additional uncertainties, because we shall depart further from the conditions of past radiological experience. Hence it is not prudent to extend the period without making some allowances for the possible increase in risk. To meet the requirements of some practical cases the following recommendation is made: *In exceptional cases in which it is necessary for a person to receive in 1 week more than the basic permissible weekly organ doses, the unit of time may be extended to 13 weeks (¼ year); provided that the dose in any organ accumulated during a period of any 7 consecutive days does not exceed the respective basic permissible weekly dose by more than a factor of three; and provided further that the total dose in any organ accumulated during a period of any 13 consecutive weeks does not exceed 10 times the respective basic permissible weekly dose.* This means, for example, in the case of the bloodforming organs, that the total accumulated dose in a period of any 13 consecutive weeks shall not exceed 3.0 rems and that the total accumulated dose in a period of any 7 consecutive days shall not exceed 0.9 rem. It will be seen that in the extreme case this permits an exposure at the rate of 0.9 rem/week (in the bloodforming organs) for 3⅓ consecutive weeks, provided in the other 9⅔ weeks of the period of 13 consecutive weeks there is no occupational exposure at all.

It will be seen that in this case the permissible total dose in a period of 13 consecutive weeks is about 25 percent lower than it would be if during this period the weekly exposure did not at times exceed the permissible weekly dose. Actually, quantitative distinctions within such close limits are not warranted by the existing state of knowledge on the subject. The reduction has been made as a matter of principle to indicate that departure from the conditions of normal radiological practice calls for additional safety factors. Extension of the dose-reckoning time from 1 day to 1 week has already raised the question of further extension. Establishment of the principle that the total dose over a given period must be decreased when the dose-reckoning period is increased serves to indicate that time extensions beyond those stipulated in this report are not worth while.

It is customary in practice to measure personnel exposure by dosimeters (such as film badges) that are read weekly or

once in 2 weeks. In such cases an uncertainty exists as to whether the total dose in *any 7 consecutive days* exceeded the permissible weekly dose. When the exposure risk is known beforehand to be low under normal working conditions, this practice is acceptable. In other cases suitable precautions should be taken to make sure that the weekly dose does not exceed the permissible weekly dose. However, occasional weekly doses in excess of the permissible weekly dose (actually or possibly) may be dealt with in accordance with the recommendations for a 13-consecutive-weeks dose-reckoning period. Thus, for example, if the personal dosimeter reading indicates that the dose accumulated over a 2-week period is three times the permissible weekly dose, the dose accumulated in 1 of the 2 weeks could not have been greater than this. This is within the limits set forth in the 13-week recommendation and is permissible when the total dose for a 13-consecutive-weeks period does not exceed 10 times the permissible weekly dose. In fact under these conditions this could occur three times in a period of 13 consecutive weeks. It is important to note, however, that this applies to cases in which "the exposure risk is known beforehand to be low under normal working conditions"; that is, when wide fluctuations in exposure rate are not likely to occur. Care should be exercised to make sure that in the example just given, the individual does not receive a dose of 0.9 r in 1 day (or in a few days) at the end of the 2-week exposure period of 1 film badge and 0.9 r in 1 day (or in a few days) at the beginning of the 2-week exposure period of the next badge, because in the 7 consecutive days at the middle of the 4-week period, the individual would then receive 1.8 r.

6.3. Nonoccupational Exposure

Because of the proximity of living quarters or other occupied regions to an X-ray installation or other source of ionizing radiation, persons not connected with radiation work may be subject to exposure. Among these may be pregnant women and children of all ages. Also, women workers may become pregnant during the period of employment. It is necessary, therefore, to consider such cases.

It is known from animal experiments that the embryo is very radiosensitive. Each organ in the embryo is most sensitive at the time it is being formed. Therefore, the damage caused by overexposure to radiation that becomes apparent after birth depends on the dose and the time of its administration during the gestation period. These periods of

especially high organ sensitivity are of different duration and occur during the first 6 months (largely during the first 3 months) in the development of the human embryo. Thereafter the sensitivity is lower but it continues to be higher than that of adults as long as there is growth. Children, therefore, can be expected to be more radiosensitive than adults. All this information has been gathered from experiments in which, of necessity, the dose was large enough to produce readily observable changes. In the case under consideration, the dose that the embryo could normally receive during the first 6 months is 7.8 r and in 9 months 11.7 r. During the periods of exceptionally high organ sensitivity—which are much shorter than the gestation period—the respective doses would be much less. *Therefore, it is not necessary to recommend for pregnant women as such, a weekly dose lower than the basic permissible weekly dose.*

From the genetic point of view the situation is quite different. If exposure of the individual starts *in utero* and continues indefinitely, the accumulated dose at the time of marriage and subsequent conception of children, is much higher than in the case of those occupationally exposed. It is also necessary to consider that some of these children may later work with radiation, in which case the period of exposure would be greatly increased. In that case the presently recommended value of the basic permissible weekly dose might no longer apply within the meaning of permissible dose, even without considering genetic effects. It will be recalled that the concept of permissible dose envisages the possibility of some radiation injury manifestable in the lifetime of the individual. The concept of permissible weekly dose is based on the interplay of deleterious action and recovery whereby the latent period for the manifestation of possible injury is stretched beyond the lifespan. The Committee has chosen numerical values of maximum permissible weekly dose under different conditions of exposure that, in the light of present knowledge, may be expected to fulfill these requirements. It is hoped that the recommended values are lower than they need be to fulfill the requirements. Prolongation of the period of exposure at the same weekly dose, will at least decrease whatever factor of safety is embodied in the present recommendations. Therefore, it is evident that steps should be taken to make sure that adults who engage in activities involving occupational exposure at permissible levels, have not been exposed during childhood and adolescence at comparable levels. Because it is impractical to keep account of the exposure of

individuals outside an area in which occupational exposure occurs, it is necessary to make sure that the weekly dose received by minors [21] outside said area be negligible insofar as subsequent occupational exposure is concerned. A factor of ten is considered satisfactory for this purpose. *Therefore, it is recommended that in cases in which minors may be exposed to radiation in the course of their normal activities, protective measures be taken to make sure that no minor actually receives radiation at a weekly rate higher than one-tenth the respective basic permissible weekly doses for the critical organs and other body tissues, according to the basic dose distribution.* "Actually" is used here to indicate that allowances may be made for the portion of the time during the week that the minors in question are not in the radiation field. Because at this weekly rate the total dose accumulated in a year is small and fluctuations from week to week are not apt to be unduly large, averaging of the weekly dose over a period of 1 year is permissible.

6.4. Number of Exposed Individuals

In the discussion of genetic effects it was pointed out that as long as the number of exposed persons is a small fraction of the total population, genetic damage to the population as a whole in future generations is not a limiting factor. For other reasons, the permissible weekly doses for occupational exposure must be set at a lower level than the criterion of genetic damage (in terms of the whole population) implied in the above statement would require. It may become necessary later to impose further restrictions on the exposure of persons in the reproductive age, in terms of a maximum accumulated dose rather than a weekly dose.

7. Noncontinuous Exposure

7.1. Temporary Exposure

Because it is generally impossible to predict how long a person may be occupationally exposed to radiation, it is prudent to assume that it may continue throughout his life. The values of the permissible weekly doses recommended in this report have been set on this basis and in accordance

[21] In this country employment of persons under 18 years of age for work with radioactive materials is prohibited by regulations promulgated by the Secretary of Labor under the Fair Labor Standards Act (see Child Labor Bulletin 101, Order No. 6). In view of this official age distinction, a minor may be assumed to be a person under 18 years of age for the purposes of the present report.

with the pertinent definitions given here, insofar as present knowledge permits. It is evident, therefore, that additional exposure to radiation will increase the potential risk. In order to facilitate discussion of the problem it is well to introduce the concept of *radiation tolerance status*.

7.2. Radiation Tolerance Status

In principle, an individual can be exposed to radiation at a certain dosage rate for the rest of his life and the dosage rate can be larger the older he is at the time the exposure starts. In the present report certain maximum permissible doses for adults exposed to radiation under various conditions are recommended. Assuming that these permissible limits will remain in force, an individual at a given age possesses something that permits him to work with (or be otherwise exposed to) radiation for the rest of his life, under the conditions prescribed at present. This something may be thought of as "the normal capacity to tolerate exposure to radiation" according to present standards, and the attribute may be called the *radiation tolerance status* of the individual. In principle any exposure in addition to that which the person received at the pertinent maximum permissible weekly doses, alters unfavorably his radiation tolerance status. It will be noted that radiation tolerance status as defined here, does not apply to genetic changes manifestable in future generations, which have been excluded for reasons already given.

In general, when such additional exposure is involved it is desirable to introduce restrictions that tend to restore the radiation tolerance status to normal in a reasonably short time. This was done, for instance, in the case of the dose-reckoning period of 13 consecutive weeks. At present, however, it is practically impossible to give quantitative expression to the requirement of compensatory measures. To establish the general principle the following recommendation is made. *Whenever for a period of time a person receives radiation at a significantly higher rate than the appropriate maximum permissible weekly doses, measures tending to restore to normal the radiation tolerance status of the exposed person shall be initiated as soon as practicable and in accordance with the state of knowledge existing at the time.* Such measures may include medical treatment and avoidance of occupational exposure to radiation for an appropriate duration of time, or simply reduction of subsequent exposure to a level below the maximum permissible weekly doses for an appropriate length of time—depending on the magnitude of

the additional doses received during the period in question and attendant circumstances. It is suggested that in such cases the measures to be instituted be determined jointly by recognized experts in medical radiology, in radiobiology, and in radiological physics.

In practice certain exceptions may be made without appreciably increasing the risk. Special cases in this category are considered in section 8, Protection Rules.

7.3. Occasional Exposure

From what is said in the preceding section, it is evident that "occasional exposure" has no place in the case of persons occupationally exposed to radiation. However, in practice there are cases in which a person may be subjected to high-level exposure for some time, occupationally or otherwise, unavoidably or unknowingly at the time. Some cases of this type will naturally fall in the category of temporary exposure, discussed above.

In general, two questions must be answered: Will the occasional exposure cause injury within a short time? If not, how will it affect the radiation tolerance status of the individual? The answer to the first question may be derived from the following quotation from the report of Andrew H. Dowdy, M. D., compiled for the Nepa Project of the U. S. Air Force, entitled "Tabulation of Available Data Relative to Radiation Biology," 1949, pp. 34–35.

> *Acute* Exposure.* Estimated results to humans exposed to filtered, 200 to 1000 kvp X-rays, measured in air.
>
> The estimates given below apply to the average normal individual. It should be borne in mind that there is considerable variation in individuals' susceptibility to radiation.
>
> (a) 25 r and below: no detectable clinical effects.
>
> (1) From animal experiments it would appear that if man behaves like the mouse and drosophila, there will be, due to radiation, a genetic effect which is much smaller than the spontaneous rate of mutations. In other words, the combined result of the spontaneous and the radiation-induced genetic abnormalities would be slightly increased but much less than double the spontaneous rate alone.
>
> (2) Delayed effects** possible but highly improbable.
>
> (b) 50 r: Slight transient reductions in lymphocytes and neutrophils. No other clinically detectable effects.
>
> (1) Incidence of radiation-induced genetic abnormalities is expected to be approximately the same or smaller than the spontaneously occurring abnormalities.

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*Received within 24 hr.

**The expression, "delayed effects," on the recipient of the radiation and as used here, refers to any harmful effects attributable to radiation, manifested at any time subsequent to the period when acute reactions may occur.

(2) Delayed effects possible but serious effects on the average individual very improbable.

(c) 100 r: At this level, nausea and fatigue may be a problem. Reduction in lymphocytes and neutrophils with delayed recovery. Above 125–150 r, vomiting may become a problem.

(1) Incidence of radiation-induced genetic abnormalities, which are quantitatively proportional to the dose, will probably still be comparable to or somewhat greater than those occurring spontaneously.

(2) Delayed effects, in summation, would be expected to shorten the life expectancy of man on the average by not more than about 1 percent from all causes, assuming that limited observations on animals can be extrapolated to man.

(d) 200 r: At this level, fatalities, 2 to 6 weeks after exposures, might occur in a small proportion of the irradiated individuals. Nausea, vomiting, and fatigue will probably occur in most persons within 24 hr. Definite depression of practically all blood elements, reduced vitality, in most cases with a convalescent period of 3 to 6 months. Temporary sterility in some cases and possibly permanent sterility in rare instances.

(1) Incidence of radiation-induced genetic abnormalities will be expected to be at least twice as frequent as the spontaneously occurring abnormalities.

(2) Delayed effects: That these would be of major consequence in a small percentage of individuals would seem very probable.

(e) 400 r: It would be expected that virtually everyone would be immediately incapacitated by such an amount of radiation, and many would never recover completely. Some deaths *would* occur in 2 to 6 weeks.

It will be noted that the above estimates are for "acute" exposures received within a 24-hr period. It can be assumed that (except for genetic consequences) if a given dose is spread over a longer period of time, its effectiveness is less. Or, in other words, to produce the same effects a larger dose is needed when the period of exposure is prolonged.

The answer to the second question is necessarily indefinite for lack of pertinent knowledge. The problem is essentially the same as the one considered in section 7.1, Temporary Exposure, and the same procedure may be followed in regard to subsequent occupational exposure. If no subsequent occupational exposure is involved, the remaining problem is to estimate what deleterious effects, if any, may develop much later in the lifetime of the individual. This again is a matter for experts to decide in the light of the best information available at the time.

7.4. Technical Overexposure

The term "overexposure" as generally used has the connotation of injury. Thus it is said that "overexposure to sunlight causes a sunburn." In the case of occupational long-term exposure to ionizing radiation a person may receive in

1 week doses larger than the pertinent maximum permissible weekly doses. In this sense it may be said that the individual was "overexposed" in that week. However, in this case the connotation of injury does not apply unless the doses were very much larger than the pertinent maximum permissible weekly doses. Accordingly, a distinction should be made between "technical overexposure" and "overexposure" in the usual sense.

8. Protection Rules

The concepts and recommendations discussed in the foregoing sections are now presented formally in the following set of Protection Rules. Interpretative comments are included to facilitate the practical application of the Rules. All technical terms and expressions used in the Rules are in accordance with the definitions given in this Handbook.

An attempt has been made to cover most of the situations arising in practice, even though it might not be possible at present to give definite values. The increased exigencies of work involving exposure to radiation have received careful consideration and special Rules have been formulated. It is realized that administrative complications have thereby been introduced, but it should be noted that they can be avoided by conducting operations according to a more general Rule. In particular it should be remembered that the Rules give maximum permissible limits, and operation at a lower level is not only permissible but desirable. Thus the differentiation according to the age of the person occupationally exposed, may be ignored completely by using the permissible levels for the younger workers. The distinction has been made because at times it is practical to delegate to older persons work involving greater radiation hazard; and this procedure is highly desirable from many points of view.

8.1. Long-Term Exposure

Rule I. Ionizing Radiation of Any Type or Types

For adults under 45 years of age whose entire body, or major portion thereof, is exposed to ionizing radiation from external sources for an indefinite period of years, the maximum permissible total weekly doses shall be 300 mrems in the bloodforming organs, the gonads, and the lenses of the eyes; 600 mrems in the skin; and the respective values of the weekly doses in millirems in all other organs and tissues

of the body according to the basic permissible dose distribution. For persons 45 years of age or older similarly exposed, the corresponding maximum permissible total weekly doses shall be double the above stated values, provided that the portion of the weekly dose in the lenses of the eyes contributed by radiation of high specific ionization does not exceed 300 mrems.

Comments. The expression "type or types" is used in order to include specifically cases of exposure to mixed radiation. The expression "total weekly dose" serves to emphasize this, but is also intended to cover cases involving exposure to radiation from internal and external sources. By major portion of the body is meant essentially the trunk and the thighs.

It is important to note that the stipulation of maximum permissible weekly doses in other organs and tissues of the body according to the basic permissible dose distribution may make the weekly dose in an organ or tissue *other than the critical organs* the limiting factor, in some cases. *Example:* Heavy ionizing particles of extremely high energy are capable of penetrating to the central region of the human body. Because the specific ionization is highest at the end of the range of such particles, the highest tissue dose and the highest specific ionization (therefore, the highest tissue dose in rems) may occur in an organ or tissue other than a critical organ, when the dose in the bloodforming organs is within permissible limits. Conceivably the local tissue dose in rems in a region beyond the assumed average depth of the bloodforming organs, may be high enough to damage some deep-seated organ, which under the usual conditions of exposure to ordinary X-rays would always receive a dose lower than the bloodforming-organ dose. The basic permissible dose distribution requires that the weekly dose at depths greater than 5 cm shall not exceed 300 mrems. Therefore, in such cases the exposure of personnel is limited by the weekly dose that the deep-seated organ or tissue in question receives. The proviso limiting to 300 mrems the portion of the weekly dose in the lenses of the eyes contributed by heavily ionizing radiation in the case of older persons, is a precautionary measure indicated by the lack of experience with *long-term* exposure of large groups to this type of radiation, which is known to be more effective than ordinary X-rays in producing cataracts.

For X-rays and beta rays an RBE of one has been recommended, irrespective of their specific ionizations. The same

value (RBE=1) applies, also, to any ionizing radiation with average specific ionization in the tissue of interest of 100 ion pairs or less per micron of water (see table 3). Therefore, the portion of the weekly dose referred to in Rule I is that delivered by densely ionizing radiation with an average specific ionization in the lens greater than 100 ion pairs per micron of water. This portion of the weekly dose in rads multiplied by the appropriate RBE from table 3 gives the weekly dose in rems, which must not exceed 300 mrems. This means for example that after age 45 a person may receive in the lenses of the eyes a weekly dose of 300 mrems (or milliroentgens) of X-rays and 300 mrems of fast neutrons.[22] It is obvious that when the whole body is exposed to both types of radiation the lens dose in effect sets the limit for the rest of the body.

It should be noted that in Rule I no distinction is made between those who have been occupationally exposed to radiation before age 45 and those who have not. Therefore, the larger maximum permissible weekly doses for older persons apply to both groups.

Because, in general, segregation according to age is impractical; the degree of protection provided in a radiation installation must comply with the more stringent requirements applicable to persons under 45. Accordingly, in practice the question arises only in special cases. The distinction has been made because at times it is practical to delegate to older persons work involving greater radiation hazard; and this procedure is highly desirable from many points of view. Also, in some cases the dose to the gonads sets the limit, and doubling the permissible dose for the gonads after age 45, would not necessarily double the exposure of other parts of the body in such cases.

Rule II. X-rays (Roentgen Rays, Gamma Rays) with Photon Energy Less Than 3 Mev

For adults under 45 years of age whose entire body, or major portion thereof, is exposed solely to X-rays with photon energies less than 3 Mev from external sources for an indefinite period of years; the maximum permissible total weekly dose shall be 300 mr measured in air at the point of highest weekly dose in the region occupied by the person, provided that the actual total weekly dose in the

[22] That is, 300 mrems delivered to the lens by protons and other recoil nuclei set in motion by the neutrons.

gonads does not exceed 300 mrads. For persons 45 years of age or older similarly exposed, the corresponding maximum permissible total weekly doses shall be double the above stated values, provided that the actual total weekly dose in the lenses of the eyes does not exceed 600 mrads.

Comments. This Rule specifically permits the measurement of weekly X-ray doses in air in a region to be occupied by the person to be protected, in accordance with present practice. It will be noted that this is limited to X-rays with photon energies less than 3 Mev. With the stipulation that the radiation dose is to be *expressed in roentgens,* exposure to multimillion-volt X-rays would not produce a dose distribution distinctly worse than that produced by supervoltage X-rays. However, as already pointed out, the dose in the bone marrow in terms of energy absorbed (rads) may be considerably higher. Because of the importance of this constituent of the bloodforming organs, it is thought best to exclude multimillion-volt X-rays.

In figure 3 are given depth-dose curves for different qualities of X-rays when the major portion of the body is exposed to a large parallel beam and the air dose is 300 mr. It will be seen that in all cases the skin dose is less than 600 mr. On the other hand, the bloodforming-organ dose—at the assumed average depth of 5 cm—is equal to or somewhat higher than 300 mr. Therefore, Rule II allows a nominal bloodforming-organ weekly dose larger than that stipulated

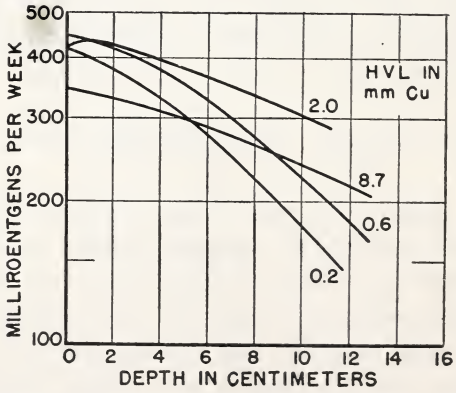

FIGURE 3. *Weekly X-ray doses received by tissues at different depths in the main portion of the body when the weekly air dose is 300 mr.*

Irradiation conditions: Stationary body; one large parallel beam perpendicular to body axis; different qualities of radiation as indicated by half-value layers (HVL) in millimeters of copper shown on curves.

in Rule I for these organs. Because the excess is not large, occurs only under certain conditions, and conforms with the experience of radiological practice; the exception is justified. It may be pointed out in this connection that if the radiation reaches the body uniformly from all directions or if the person turns his body constantly with respect to a single parallel beam of radiation, during the exposure, all tissue doses in roentgens are less than the air dose in the same region. In general the conditions of exposure in practice lie between the two extremes of a fixed position in a parallel beam and uniform irradiation from all directions, and the bloodforming-organ weekly dose (at the assumed depth of 5 cm) would exceed 300 mr only in special cases.

What has just been said about the bloodforming organs applies to the ovaries, which in reality are at a greater depth than 5 cm. In general, therefore, the *actual* weekly dose in the ovaries may be assumed not to exceed 300 mr when the weekly air dose in the region to be occupied by the person is 300 mr. However, the proviso has been added to make sure that the weekly dose in the testes does not exceed 300 mr under special conditions of exposure in the case of men.

Rule II permits exposure of the lenses of the eyes of persons under 45 at a weekly rate considerably in excess of 300 mr; that is, a maximum of about 450 mr/week in the worst case of direct exposure to X-rays for which the backscatter is 50 percent. This is justified because Rule II applies only to X-rays and, as stated previously, the lens of the eye is not particularly sensitive to X-rays. For persons 45 years of age or older the weekly dose in the lenses of the eyes is specifically limited to 600 mrads.

Rule III. Radiation of Very Low Penetrating Power (Half-value Layer Less Than 1 mm of Soft Tissue)

For adults of any age whose entire body, or major portion thereof, is exposed to ionizing radiation of very low penetrating power from external sources for an indefinite period of years; the maximum permissible total weekly dose in the skin shall be 1500 mrems, provided that the total weekly dose in the lenses of the eyes does not exceed 300 mrems.

For the purposes of this Rule ionizing radiation is of very low penetrating power when the tissue dose *in rems* decreases with depth at the rate of at least one-half per millimeter of soft tissue; so that the tissue dose in rems at a depth of 3 mm is not greater than one-eight (⅛) the tissue dose in rems in the basal layer of the epidermis.

Comments. The penetrating power of the radiation has been limited intentionally to the extent necessary to prevent exposure of the lenses of the eyes at a rate higher than the permissible 300 mrems/week. Nevertheless a specific restriction to this effect is included in the Rule. If adequate and positive provisions to protect the lenses of the eyes were made, the penetrating-power restriction could be relaxed somewhat. In the ultimate analysis, an arbitrary limit must be set. The chief merit of the present one is that it covers most practical cases (e. g., exposure to low-energy beta rays) without requiring special protection of the eyes.

It will be noted that in this case the permissible weekly doses are the same for adults under and over 45 years of age.

Rule IV–A. Local Exposure of the Hands and Forearms to Any Ionizing Radiation

For adults of any age whose hands and forearms are exposed to ionizing radiation from external sources for an indefinite period of years; the maximum permissible total weekly dose shall be 1,500 mrems in the skin, provided the respective weekly doses in millirems in all other tissues of the hands and forearms are not in excess of those that would result from exposure to ordinary X-rays at a weekly dose of 1,500 mr in the skin.

Comments. The proviso is added in order to make sure that the deeper tissues do not receive excessive weekly doses. This could happen in some very special cases of exposure to high-specific-ionization radiation, in which the range of the monoenergetic particles would terminate in the deeper tissues. It could also happen in the forearms with multimillion-volt X-rays of suitable photon energy.

In the case of exposure to X-rays of any photon energy, these complications cannot occur *when the weekly dose for the skin is specified in roentgens* [23] because the measurement must be made with the radiation in equilibrium with its corpuscular emission. Therefore, in the case of X-rays a simpler Rule may be formulated.

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[23] The only exception to this statement is that the dose in the bone marrow might be higher in the case of multimillion-volt X-rays owing to the long range of the electron-positron pair produced in bone—as discussed earlier.

Rule IV–AX. Local Exposure of the Hands and Forearms to X-rays (Roentgen Rays, Gamma Rays) of Any Photon Energy

For adults of any age whose hands and forearms are exposed solely to X-rays from external sources for an indefinite period of years, the maximum permissible total weekly dose shall be 1,500 mr in the skin.

Comments. Attention may be called to general stipulations made earlier in this Handbook that the pertinent weekly dose is the one in the basal layer of the epidermis (at a depth corresponding to 7 mg/cm^2) in the significant skin area that receives the highest weekly dose

It shall be definitely understood that total weekly dose in this case (as well as in the case of Rule IV–A) means the sum of weekly doses resulting from whole-body and local exposures, whether they take place simultaneously or in succession.

Rule IV–AX is intended to apply primarily to persons handling radioactive isotopes at close range. Therefore, beta radiation may also be present. In such cases the total weekly dose shall include both contributions and the applicable rule is Rule IV–A. The summation may be made in terms of tissue dose in rads in the basal layer of the epidermis for both gamma rays and beta rays, because in this case a weekly dose in rads is assumed to be numerically equal to the same weekly dose in rems. When the area that receives the highest weekly dose is essentially limited to the fingers, the gamma-ray weekly dose in rads in the skin may be assumed to be numerically equal to the weekly dose in roentgens, measured in air in the appropriate region. In this case backscatter is small and may be neglected.

Rule IV–B. Local Exposure of the Feet and Ankles to Any Ionizing Radiation

For adults of any age whose feet and ankles are exposed to ionizing radiation from external sources for an indefinite period of years; the maximum permissible total weekly dose shall be 1,500 mrems in the skin, provided the respective weekly dose in millirems in all other tissues of the feet and ankles are not in excess of those that would result from exposure to ordinary X-rays at a weekly dose of 1,500 mr in the skin.

Rule IV–BX. Local Exposure of the Feet and Ankles to X-rays (Roentgen Rays, Gamma Rays) of Any Photon Energy

For adults of any age whose feet and ankles are exposed solely to X-rays from external sources for an indefinite period of years, the maximum permissible total weekly dose shall be 1,500 mr in the skin.

Rule IV–C. Local Exposure of the Head and Neck to Any Ionizing Radiation

For adults whose heads and necks are exposed to ionizing radiation from external sources for an indefinite period of years; the maximum permissible total weekly doses shall be 1,500 mrems in the skin and 300 mrems in the lenses of the eyes, provided the respective weekly doses in millirems in all other tissues of the head and neck are not in excess of those that would result from exposure to ordinary X-rays at a weekly dose of 1,500 mr in the skin. For persons 45 years or older the weekly dose in the lenses of the eyes may be 600 mrems, provided that the portion contributed by radiation of high specific ionization does not exceed 300 mrems.

Comments. It is obvious that the stipulation of a weekly dose not in excess of 300 mrems in the lens of the eye (for persons under 45) makes this rule applicable only when the radiation is of low penetrating power (e. g., beta rays); then absorption in the intervening tissues of the eye reduces the lens dose sufficiently, or it makes feasible the wearing of goggles of sufficient absorbing power to bring about the same result. It will be noted, however, that this Rule is not so restrictive as Rule III, which applies to exposure of the skin of the whole body. Assuming that the eyes can be properly shielded (or are not in the radiation beam), the weekly doses received by other tissues in the head and neck could then be considerably higher than those permitted by other Rules.

Rule IV–CX. Local Exposure of the Head and Neck to X-rays (Roentgen Rays, Gamma Rays) of Any Photon Energy

For adults whose heads and necks are exposed solely to X-rays from external sources for an indefinite period of years; the maximum permissible total weekly doses shall be 1,500 mr in the skin and (a) 450 mr in the lenses of the

eyes of persons under 45 years of age, (b) 600 mr in the lenses of the eyes of persons 45 years of age or older.

Comments. The relaxation in permissible weekly dose for the lenses of the eyes of persons under 45, embodied in this Rule, is justified because it deals with exposure to X-rays only. A weekly dose of 450 mr in the lens is permitted by Rule II. For persons 45 years of age or over a weekly dose in the lens of the eye of 600 mr is permitted by Rule I and Rule IV–C, because in the case of X-rays 1 r produces a tissue dose not greater than 1 rem in soft tissues.

General Comments on Rules IV. Mention has been made that total weekly doses specified for local exposure include those resulting from whole-body exposure. The question now arises as to whether all these local exposures, as well as general body exposure, are permitted to take place concurrently. Because no large volumes of tissues (particularly of the bloodforming organs) are involved in the local exposures, and provisions have been made for protection of sensitive tissues, concurrent exposure is permitted. It is obvious, of course, that such spotty exposure is not likely to occur in practice. In close-range work with radioactive isotopes, for instance, the local exposure would be essentially limited to the hands. The feet and ankles may be exposed locally in decontaminating a floor on which radioactive material has been spilled accidentally.

Rules IV take care of the most common cases of local exposure encountered in practice. Logically local exposure of other body regions (of small area) at weekly doses higher than those stipulated for whole-body exposure should also be permitted. However, it is evident that the addition of local exposures cannot go on indefinitely. Furthermore, to permit local exposure of regions in the major part of the body, so many restrictions would have to be imposed that the small addition in permissible local dose would be of little practical value.

8.2. Occasional Exposure

Rule V–A. Accidental or Emergency Exposure to X-rays (Roentgen Rays, Gamma Rays) with Photon Energy Less Than 3 Mev

Accidental or emergency exposure of the whole body of adults or parts thereof to X-rays with photon energy less than 3 Mev, from external sources, *occurring only once in the lifetime of the person,* under the conditions and in the

respective dosages stated below, shall be assumed to have no effect on the radiation tolerance status of that person.

(a) Exposure of the whole body—any adult. Total dose, measured in air: up to 25 r.

(b) Local exposure—any adult. Dose measured in air and additional to whole-body dose: (1) Hands and forearms, up to 100 r; (2) feet and ankles, up to 100 r.

Emergency as used here refers to a combination of adverse circumstances arising unexpectedly, which, if left uncorrected would have the potentiality of seriously endangering health and/or property. It does not refer to conditions of warfare. An emergency exposure, therefore, is one incurred in the performance of an unusual task to protect the individual himself or others, or valuable property.

It is envisaged that emergency exposure may occur by prearranged plan. In general it is impossible in such cases to determine accurately beforehand the doses that the person may receive, and conceivably they may be underestimated by a factor of two. Rule V–B will serve as a guide in such cases.

Rule V–B. Planned Emergency Exposure

Emergency work involving high-level exposure to X-rays with photon energies less than 3 Mev shall be carried out on the basis that the person will not receive doses higher than one-half the respective doses stipulated in Rule V–A. If the doses actually received in the performance of such work do not exceed the respective maximum doses stipulated in Rule V–A, the exposure may be considered to be in the category covered by Rule V–A. Women of reproductive age shall not be subjected to planned emergency exposure.

Comments on Rules V–A and V–B. The difference between accidental and emergency exposures can be brought out by a simple example. If the energizing switch of an X-ray machine fails to shut off the power and, not knowing this beforehand, a technician enters the treatment room; the exposure is accidental. If on the other hand, through some fault in the switch, the technician cannot turn the machine off and he enters the treatment room to prevent overtreatment of a patient; he gets an "emergency" exposure.

"Once in a lifetime" requires careful consideration. Accidental or emergency exposures should not occur frequently, of course, but in spite of all precautions they may occur

more than once in the lifetime of an individual. Reasonably, if a body dose of 25 r received all at once is considered to have no effect on the radiation tolerance status, two doses of 12.5 r each separated by a short or a long interval, or other fractionated exposures of the same total dose, should be negligible, also. Whether this is so or not is immaterial, because it is impractical (although desirable) to keep account of such exposures over a long period of time—especially when the worker changes places of employment. Therefore, "once in a lifetime" should be interpreted to mean one episode in a lifetime. The duration of the episode may be anything up to 1 month, to take care of a situation in which the exposure at the higher rate may not be discovered and remedial measures may not be taken for some time. The individual concerned should know the nature of the accidental or emergency exposure and the doses involved. It shall be his responsibility to inform his present and his future employers of such occurrence.

It should be noted that the chief purpose of Rules V–A and V–B is to provide guidance in cases in which employees have received, in some unusual way, more radiation than the general permissible weekly doses would allow. The Rule specifically permits continuation of occupational exposure at the same rate as before the episode, provided the accidental or emergency exposures do not exceed the stipulated doses. What to do if a second exposure episode should occur depends on too many factors to permit generalization. Certainly if a person has too many accidents he should not work with ionizing radiations. At any rate, in reaching a decision, account should be taken of previous exposure history and future exposure potential. It is highly desirable in such cases to refer the problems to recognized experts in medical radiology, in radiobiology, and in radiological physics for joint consideration.

In this connection it is well to call attention to the general recommendation on compensatory measures in cases of technical overexposure (for definition, see section 7.4). Rule V–A applies to an exposure *occurring only once in the lifetime of the person*. In the over-all picture of occupational exposure during the working life of the individual, a dose of 25 r may well be disregarded. Therefore, it may be *assumed* to have no effect on the radiation tolerance status of the person. In reality, however, it does influence the radiation tolerance status, otherwise there would be no reason for not permitting a repetition of a similar exposure. Accordingly, it is generally desirable to institute compensatory measures in such

cases. This is particularly true when the conditions of occupational exposure are such that the possibility of recurrence of technical overexposure cannot be excluded.

"Total dose" as used in Rules V–A and V–B means the integrated dose for the period of the episode. The dose resulting from normal exposure at permissible dosage rates during the same period (maximum of 1 month) is negligible in comparison and need not be taken into account.

In the case of local exposure in Rule III, the stated doses are "in addition to whole-body doses." This means that the hands could receive a dose of 125 r during the episode. No additional dose is specified for the head, because of the present uncertainty concerning radiation-induced cataracts.

Rule V–C. Accidental or Emergency Exposure to Other Types of Ionizing Radiation

Rules V-A and V-B are applicable to accidental or emergency exposure to ionizing radiation of any type and energy when the tissue doses resulting therefrom in the different organs and tissues of the body (expressed in rems) do not exceed numerically the respective tissue doses in rads resulting from exposure to X-rays with photon energy less than 3 Mev, under the conditions stipulated in Rule V-A; provided, however, that the portions of the respective tissue doses in rems contributed by radiation of high specific ionization do not exceed 50 percent of the total tissue doses.

In the category of occasional exposure may be included exposures incurred for medical reasons. In general these are local exposures involving low doses and may be disregarded. In some special cases large volumes of tissue may receive fairly large doses repeatedly as a result of diagnostic or therapeutic procedures, and prudence demands that they be taken into account. This is particularly true in cases in which accidental or emergency exposure has occurred, let us say, within 3 months. In any such case the radiologist should be given all pertinent data regarding the previous radiation-exposure history of the individual. The radiologist on his part should give the patient and his employer all pertinent data concerning the exposures to X-rays for medical purposes. Rule VI below will serve as a guide.

Exposure of any part of the body to X-rays resulting from ordinary medical diagnostic procedures shall be assumed to have no effect on the radiation tolerance status of the person concerned, provided that no contributory accidental or emergency exposure of the order of magnitude specified in Rules V has occurred within the previous 3 months.

Comments: "Ordinary medical diagnostic procedures" include all X-ray examinations except fluoroscopic examinations of the internal organs of the trunk *repeated* within a period of 1 month. If the total radiation dose from such fluoroscopic examinations in 1 month does not exceed the whole-body dose specified in Rule V–A, it may be disregarded insofar as the radiation tolerance status of the person is concerned in his occupational exposure. For this purpose doses resulting from fluoroscopic examinations of the chest and of the abdomen are not to be added, because different regions of the body are irradiated.

"Contributory" in Rule IV is used to indicate that the accidental or emergency exposure does not always constitute a contributory factor. Thus, an accidental exposure *limited to the hands* contributes nothing to the dose resulting from a fluoroscopic examination of the gastrointestinal tract.

For the purposes of Rule VI, X-ray doses due to diagnostic procedures shall be reckoned in terms of the air dose on the incidence side of the patient's body at the center of the irradiated field.

It is important to remember that the recommendations embodied in these Protection Rules relate to occupational exposure of a small fraction of the population. Exposure to X-rays for medical reasons involves other persons as well. Therefore, medical exposure cannot be disregarded in arriving at an average dose for the whole population. In this case, however, genetic damage to the population as a whole in future generations is paramount and the doses received by the gonads are the significant ones. Accordingly in order to maintain the accumulated gonad dose per individual of the whole population of reproductive age within desirable limits, it is important to avoid or minimize as far as practicable exposure of the gonads in medical practice.

9. Summary

The present report deals primarily with the protection of persons occupationally exposed to ionizing radiation from external sources. An attempt has been made to cover most of the situations encountered in practice. However, it has not always been possible to make recommendations in quantitative terms. In such cases the recommendations are intended to serve as practical guides. In justification of this procedure it may be pointed out that no useful purpose is served by ignoring difficult situations that in practice require action. In any case the recommendations are based on presently available information and cannot be regarded as permanent. For this reason and on general grounds it is strongly recommended that exposure to radiation be kept at the lowest practicable level in all cases.

In the formulation of the recommendations and protection rules given in this Handbook, emphasis has been placed on the deleterious effects of ionizing radiation manifestable in the lifetime of the individual. Genetic changes possibly injurious to the race as a whole in future generations have been considered, but they do not constitute the limiting factor in setting up permissible levels of occupational exposure, under present conditions.

It is obvious that any significant departure from the environmental conditions in which man has evolved may entail a risk of possible deleterious effects. Scientifically speaking, therefore, it must be assumed that long-continued exposure to ionizing radiation at a dosage rate higher than that due to the natural radioactivity of the earth and cosmic rays involves some risk. Because no radiation level higher than the natural background can be regarded to be absolutely "safe," the problem is to choose a practical level that, in the light of present knowledge, involves a negligible risk. It is appropriate to call this a "permissible" level, which for convenience is expressed as a permissible weekly dose.

Permissible weekly dose. A permissible weekly dose is a dose of ionizing radiation accumulated in 1 week of such magnitude that, in the light of present knowledge, exposure at this weekly rate for an indefinite period of time is not expected to cause *appreciable bodily injury* to a person at any time during his lifetime.

As used here "appreciable bodily injury" means any bodily injury or effect that the average person would regard as being objectionable and/or competent medical authorities

would regard as being deleterious to the health and well-being of the individual.

Dose is used in its radiological sense and particularly as tissue dose in the irradiated tissue, organ, or region of interest.

One week means any 7 consecutive days, not necessarily a calendar week.

Maximum permissible weekly dose. In principle there is a maximum weekly dose that just fulfills the requirements set forth in the definition of permissible weekly dose. Any smaller weekly dose, obviously, would also meet the requirements. Therefore, in protection rules or recommendations in which numerical values of permissible weekly doses are given, the values are the highest ones permissible *under the stipulated conditions of exposure.* To bring this out explicitly they are called "maximum permissible weekly doses."

Critical organs and effects. In the past, occupational exposure has been limited largely to X-rays, and the permissible daily dose has been expressed in terms of air dose in roentgens. Extension to other types of ionizing radiation necessitates consideration of the absorbed doses actually received by different organs of the body. Experience has shown that certain organs are particularly vulnerable. The following organs and potential late effects are considered critical from the point of view of protection: (a) Skin with respect to cancer, (b) bloodforming organs largely with respect to leukemia, (c) gonads with respect to impairment of fertility, and (d) eyes with respect to cataracts.

Dose in an organ. Some organs, such as the bloodforming organs, are widely distributed in the body and it is difficult to decide what constitutes the organ dose. Obviously an averaging process is involved whereby at every point of the organ account is taken of the local dose and its potentiality for harm to the organ. This is impractical if not impossible, but it may be taken as the ideal to be approached by suitable approximations.

When the whole body is exposed to penetrating radiation, the approximation may be made on the basis of an average or effective depth of the organ below the surface of the skin.

When the spatial distribution of radiation in the organ is very nonuniform, an average of the physical dose is not necessarily indicative of the potential damage to the organ in its relation to the normal physiological functions of the body as a whole. Therefore, in such cases it is necessary to consider a local region of the organ in which the dose is highest. This may be called the significant volume.

Basic permissible weekly doses in roentgens assigned to the critical organs. In the light of present knowledge the values of the permissible weekly doses for the critical organs tabulated below are thought to be well below the limits indicated by the definition of permissible weekly dose. The values apply to the whole organs when the distribution of radiation is substantially uniform, or to the specified significant volumes when the radiation is more or less localized in parts of the organs. These values are based on whole-body exposure to ordinary X-rays (q. v.).

Organ[a]	Basic permissible weekly dose	Significant volume (or area) in the region of highest dosage rate	Assumed average depth (for purposes of calculation)
	mr		
Skin	600	1 cm^2	7 mg/cm^2.
Bloodforming organs.	300	1 cm^3	5 cm.
Gonads:			
Ovaries	300	10 percent of total volume.	7 cm.
Testes	300	10 percent of total volume.	Variable, depending on conditions of exposure. Minimum: 1 cm.
Lenses of the eyes.	300	Volume of either lens.	3 mm.

[a] Other organs and tissues of the body according to the Basic Dose Distribution Curve of figure 2.

Basic permissible weekly doses in rads for exposure to X-rays. The basic permissible weekly dose in rads for each critical organ or tissue is that produced therein by the respective basic permissible weekly organ dose or tissue dose in roentgens for whole-body exposure to ordinary X-rays.

For the purposes of this Handbook it shall be assumed that the basic permissible weekly organ dose or tissue dose in rads is numerically equal to the respective basic permissible weekly organ dose or tissue dose in roentgens, for all X-rays with photon energies less than 3 Mev. This means that for all X-rays of photon energies less than 3 Mev, the basic permissible weekly organ doses in *millirads* are taken to be respectively numerically equal to those in milliroentgens listed in the above table.

Guiding principle for transition to other photon energies and other types of radiation. The potential risk of exposure to radiation of any type and energy should not be greater

than that involved in exposure to ordinary X-rays under comparable conditions.

The rem. The rem is the quantity of any ionizing radiation such that the energy imparted to a biological system (cell, tissue, organ, or organism) per gram of living matter by the ionizing particles present in the region of interest has the same biological effectiveness as an absorbed dose of 1 rad of X-radiation with average specific ionization of 100 ion pairs per micron of water in the same region.[24]

Conversion factors for radiation of high specific ionization. When the average specific ionization of heavy ionizing particles is more than 100 ion pairs per micron of water, it shall be assumed that a dose of D rads produces a dose of D+(RBE) rems; in which RBE stands for the appropriate value of the biological effectiveness of the radiation in question relative to that of X-radiation with an average specific ionization of 100 ion pairs per micron of water, for the particular biological system and biological effect under consideration and for the conditions under which the radiation is received.

For the purposes of this Handbook it may be assumed that the values of the RBE given in table 3 apply to all conditions of external exposure.

Extension to all ionizing radiations. For exposure to any ionizing radiation the respective permissible weekly doses (or total doses in a period of time, as the case may be) for the different tissues and organs of the body expressed in rems shall be numerically equal to the appropriate permissible doses for exposure to ordinary X-rays expressed in rads. This means in particular that for all ionizing radiations the basic permissible weekly organ doses in *millirems* are respectively numerically equal to those in milliroentgens listed in the table on page 76.

Total tissue doses. It shall be understood that, unless stated otherwise, all permissible doses are total doses resulting in the region of interest from simultaneous or successive exposures to one or more types of radiation from external or internal sources.

Determination of tissue doses and accuracy. Measurements of air doses or tissue doses in roentgens shall be made under the conditions existing in the place of interest and in accordance with the requirements of the definition of the roentgen.

Measurements of tissue doses in rads shall be made under the conditions existing in the place of interest, with instruments that permit the evaluation of the energy imparted to

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[24] See comments in section 5.2.c, on calculation of average specific ionization.

the tissue in question by the ionizing particles of the radiation.

Because it is not always practicable to make such measurements, tissue doses in rads may be determined indirectly. In such cases the methods and constants used shall be those generally accepted by experts in this field at the time of interest.

The accuracy of measurements or indirect determinations of tissue doses shall be as high as accepted practice permits at the time of interest. At any rate, proper allowances for possible errors shall be made to make sure that the actual doses to be received by a person cannot exceed the maximum permissible limits.

Modified permissible doses. Practical considerations make it desirable to recommend permissible doses that differ materially from the basic permissible doses, in cases in which this may be done without appreciably increasing the risk. Some special cases are considered below according to modifying factor.

Limited region of body. Three cases of local exposure, (1) hands and forearms, (2) feet and ankles, and (3) head and neck, are covered by special rules (see Rules IV).

Radiation of low penetrating power. See Rule III.

Weekly dose fluctuations. In cases in which it is necessary for a person to receive in 1 week more than the permissible dose, the unit of time may be extended to 13 weeks; provided that the dose accumulated during a period of any 7 consecutive days does not exceed the appropriate permissible weekly dose by more than a factor of three and provided further that the total dose accumulated during a period of any 13 consecutive weeks does not exceed 10 times the permissible weekly dose.

Nonoccupational exposure of minors. It is recommended that in cases in which minors may be exposed to radiation in the course of their normal activities, protective measures be taken to make sure that no minor actually receives radiation at a weekly rate higher than one-tenth the respective basic permissible weekly doses for the critical organs.

Number of exposed individuals. At present the number of persons occupationally exposed to radiation is very small in comparison to the total population of the country, and therefore the dose per individual of the whole population is correspondingly small. Thus genetic damage to the population as a whole in future generations from occupational exposure is not now a limiting factor. It may become necessary later to impose further restrictions on the expo-

sure of persons in the reproductive age, in terms of a maximum accumulated dose rather than a weekly dose.

Temporary exposure. Because it is generally impossible to predict how long a person may be occupationally exposed to radiation, it is prudent to assume that it may continue throughout his life. Therefore, "temporary" exposure at levels higher than the permissible weekly dose should not be permitted. If it does occur it must be assumed in general that it alters unfavorably the radiation tolerance status of the individual; and measures tending to restore it to normal shall be initiated as soon as practicable, in accordance with the recommendations of experts.

Occasional exposure. In general, occasional exposure will also alter unfavorably the radiation tolerance status of the individual. Some cases of this type will naturally fall in the category of temporary exposure and have already been covered.

In other cases it may be a matter of deciding whether "immediate" injury is to be expected or to what extent the radiation tolerance status of the individual will be affected. Estimates of effect to be expected from acute exposures of different magnitudes are quoted from Dr. Andrew H. Dowdy's Nepa Report of 1949, to serve as a guide (see page 59).

Cases of occasional exposure in which it may be assumed that the radiation tolerance status of the individual has not been affected are considered under Rules V and VI.

As the applications of atomic energy expand and the number of exposed individuals increases, genetic effects will become more important. Accordingly, it may be expected that at some time in the not-too-distant future a reappraisal of the situation will become necessary. On the basis of present knowledge of the genetic effects of radiation, it may be predicted that any future revision of permissible doses to the gonads of young persons will be downward. This should be borne in mind and unnecessary exposure to radiation should be avoided at all times.

Submitted for the National Committee on Radiation Protection.

LAURISTON S. TAYLOR, *Chairman.*

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